Importing experimental results via S2D model in ADS tool for Power Amplifier Design

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Research Article

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Importing experimental results via S2D model in ADS tool for Power Amplifier Design

Design, Simulation and Performance Investigation

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Abstract In this paper, behavioral modelling of a power amplifier is implemented by using S2P and S2D model setup. By using the standard power amplifier for obtaining the measured results of Scattering (S-parameters and large signal parameters. These parameters are imported into the S2P and S2D model to perform the small signal and large signal analysis at 3 GHz frequency. Then, the simulated results are compared with the measured results to verify the efficient utilization of behavioral models. The novelty of this work deals with the simulation study of the characteristics of a silicon-based driver amplifier which are obtained directly from the measurements. This work can be utilized to determine the influence of the driver amplifier properties on the power amplifier measurements via simulation. At last, the study of relative error performance analysis between measured and simulated results of different parameters is carried out and calculated of NMSE (in %) for S11, S12, S21, S22, gain, pout, 1 dB compression point, ACP, 3^{rd} harmonics, 4^{th} harmonics, and 5^{th} harmonics are 0.0083, 0.0055, 0.0086, 0.011, 0.0844, 0.814, 0.926, 0.71, 0.22, 0.012 and 0.070 respectively.

Keywords Power amplifier, Small signal analysis, Large signal analysis, Network analyzer, Radio-frequency.

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1 Introduction

In modern times, Power amplifier (PA) has become the most demanding and promising circuit topology in the field of advanced wireless technology for efficient energy consumption and low transmitting expenses. With the utilization of circuit level [7, 10] or behavioral models [9, 3, 1] a veracious modelling technique is required in the design of power amplifier. As compared to circuit-level models, behavioral models are much preferred because of the easy modelling method. The basic behavioral modelling of power amplifier includes small signal analysis. From this, small signal gain and basic linearity analysis can be carried out. However, a complete nonlinear analysis of the device under test (DUT) cannot be performed. Therefore, to study the accurate nonlinear behavior of power amplifier, large signal analysis is required [4]. Furthermore, for the characterization of power amplifier, behavioral models with some mathematical formulation must be included. Most of the simulation and computer-aided engineering-based software such as Keysight's Advanced design system (ADS) is utilized to furnish the in-built behavioral models (such as S2D and P2D models) of PA with S-parameters [11, 5], 1 dB gain compression point and third order intercept point (IP3) for analyzing the large signal simulation. In this work, importing of S2P and S2D models is being employed for characterization and measurement of the power amplifier. By using the behavioral model of PA, it is quite straightforward to perform the small signal and large signal simulation. The paper is organized as follows: Section II describes the basic structure of S2D modelling. Section III describes the measurement setup and the related procedures. Section IV presents the results and the discussion and finally, Section V concludes the paper.

2 Proposed Model and Configuration

There are many behavioral model examples available in the electronic design automation (EDA) tool for the extraction of small signal and large signal parameters. In the ADS environment, the S2P model is available for small signal analysis of active and passive element-based circuits [8]. Here, All the S-parameters i.e., input return loss (S11), small signal gain (S21), output return loss (S22), and insertion loss (S12) can be extracted by performing the S-parameter analysis for a particular range of frequency. For large signal analysis, the AMPS2D model setup is available in the ADS tool. Here, Radio-frequency (RF) parameters can be extracted by simulating the harmonic balance of the AMPS2D model setup containing the S2D file from the measured large signal parameters data. The basic flowchart of the S2P and S2D model-based simulation setup is given in Figure 1.

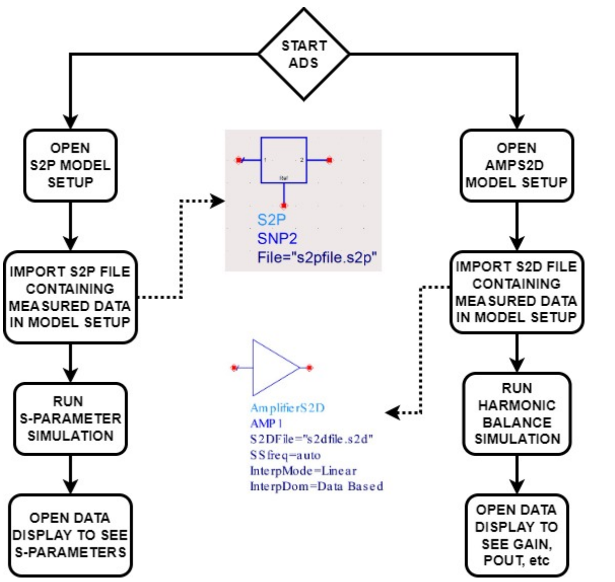

Fig. 1 General structure of S2P and S2D modelling.

2.1 Steps for S2P model setup

1. First, start the ADS with the design environment window and open the S2P model setup in the schematic cell view.
2. Then, prepare the S2P file with the measured data in a predefined format and import it into the S2P model setup.
3. Start the S-parameter simulation to perform the small signal analysis.
4. Lastly, open the data display window to see the simulation result of S-parameter.

2.2 Steps for S2D model setup

1. First, start the ADS and open the schematic window in the ADS design environment.
2. Then, prepare the S2D file in the predefined format according to the measured data type and import it into the S2D model setup.
3. Start the Harmonic Balance (HB) simulation to perform the large signal analysis (namely one-tone and two-tone HB simulation).
4. Lastly, open the data display window to see the simulated results of 1-tone and 2-tone analysis in a separate window.

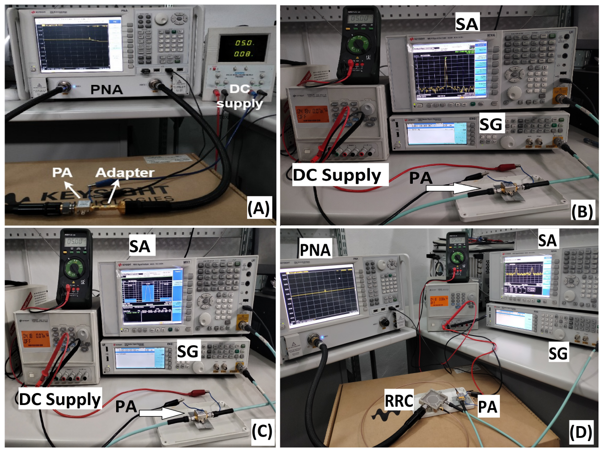

Fig. 2 (A) Measurement setup configuration (B) Measurement setup of 1-tone analysis for output spectrum of PA (C) Measurement setup of 1-tone analysis of PA (D) Measurement setup of 2-tone analysis of PA for third order intercept (TOI).

3 Measurement Procedure

The measurement setup for small signal and large signal analysis can be performed for analyzing the nonlinear characteristics of RF PA (ZX-60-63+) from Mini-circuits [2] biased at 5V,80 mA as shown in Figure 2(A).

3.1 Small signal analysis of PA

The small signal parameters (S-parameter) are measured by performing the small signal analysis of RF PA. The measurement setup for S-parameter analysis consists of PNA network analyzer N5221A, RF testing cables, and RF PA. After completing the calibration of PNA for 2 ports [6], all the S-parameters are measured for the frequency ranging from 50 MHz to 8 GHz with a step of 500 MHz. The measured S-parameters are saved in .csv file format. Then, the S2P file containing measured S-parameters of standard PA is imported into the

S2P model of the ADS software, and the small signal analysis within the same frequency range for 50-ohm termination. All the simulated S-parameters are available in the data display window of the simulated cell view.

3.2 Large signal analysis of PA

The measurement setup is the same as the small signal analysis. The only difference is that all the measurements are carried out with power sweep instead of frequency as in the case of small signal characterization. On PNA setup, Gain compression analysis (GCA) is performed. The gain of PA is calculated by using equation 1. The measurement of large signal analysis can be performed in two ways i.e. one tone and two tones. The description of measurement setup and procedure of 1-tone and 2-tone analysis of PA is given in sections 3.2.1 and 3.2.2 respectively.

$$\mathrm{Gain(dB)} = \mathrm{P_{OUT}[dBm]} - \mathrm{P_{IN}[dBm]} \quad (1)$$

3.2.1 1-tone analysis of PA

The 1-tone PA measurement setup consists of a DC supply with multi-meter, MXA N9020A spectrum analyzer (SA), EXG N5172B signal generator (SG), and PA. The large signal parameters are measured by selecting the standard gain compression mode for the swept input power per frequency. For this type of measurement, input power coming from port 1 of PNA is swept from -30 dBm to 20 dBm with a step of 0.2. Port 2 of PNA is connected to the other terminal of PA to display the measurement results. Figure 2(B) shows the output spectrum of PA biased at 5V, 80 mA for 3 GHz frequency. Figure 2(C) shows the Adjacent channel power (ACP) analysis of PA biased at 5V,80 mA for 3 GHz frequency.

The measured large signal parameters can be saved in .csv file format. The exported data contain the measured output power with respect to input power. Then, the measured data are saved in the S2D file format, which contains both the S-parameters (as explained in section 3.1) and large signal parameters (Gain, output power, Harmonics,etc.) with respect to the swept input power for 3 GHz frequency. Then, this S2D file is imported into the behavioral model of PA given in ADS tool i.e., S2D model. Finally, the simulation setup of large signal analysis of PA having HB simulator with swept power and imported S2D file-based amplifier model is run to perform the simulation.

3.2.2 2-tone analysis of PA

The 2-tone PA measurement setup consists of DC supply with a multimeter, spectrum analyzer (SA), signal generator (SG), Rat-race coupler (RRC) as power combiner [12], and PA biased at 5V, 80 mA. For 2-tone analysis, both the PNA and SG are set with the same amplitude of input power of 5 dBm. But, the operating frequency of PNA and SG is set at 3.01 GHz and 2.99 GHz respectively. One signal is given to port 1 of RRC and the other one is given to port 3 of RRC. The RRC acts as a power combiner between the power signals of port 1 and port 3. The resultant output is a combined power signal, which is taken out from port 3 and given to the SA. It is noted that port 4 is kept isolated for the entire measurement procedure. The whole measurement procedure is carried out at center frequency of 3 GHz with frequency spacing of 20 MHz. The display of the measured two-tone spectrum is shown in Figure 2(D).

4 Results and Discussion

In this section, PA measurements and simulation results of S-parameters as well as gain and output power versus input power are discussed as shown in Figure 3(A) and Figure 3(B). The value of output power is 15.94 dBm for 0 dBm input power and the corresponding gain is 15.90 dB. It is observed that the output power of the PA is increasing up to 5 dBm input power. After the further increase in input power, the value of output power becomes saturated which is said to be saturated power (Psat). The 1 dB compression is normally defined as the corresponding output power for which the gain drops by 1 dB. Here, the 1 dB compression point at 5 dBm input is 24.4 dBm. The value of measured and simulated gain of the PA is constant up to 0 dBm input power. After that, the value of gain starts decreasing linearly on increasing the swept input power. The trajectory of the slope of gain is opposite to the slope of the output power. This can be clearly explained by seeing the gain expression in Eq. 1.

Also, after the completion of the measurement of ACP analysis at 3 GHz, 5 dBm input power signal, obtained ACP is -65.8 dBc. Figure 3(C) shows measured and simulated results of the 3^{rd} harmonics, 4^{th} harmonics, and 5^{th} harmonics for different values of output power. It is observed that values of 3^{rd} harmonics and 5^{th} harmonics are more than -20 dBc which is required for better linearity of PA. Figure 3(D) shows the measured and simulated results of the output spectrum for the two-tone analysis of PA. By observing the results, it is seen that the value of output power for two tone frequencies (2.99 GHz and 3.01 GHz) is 22.91 dBm and

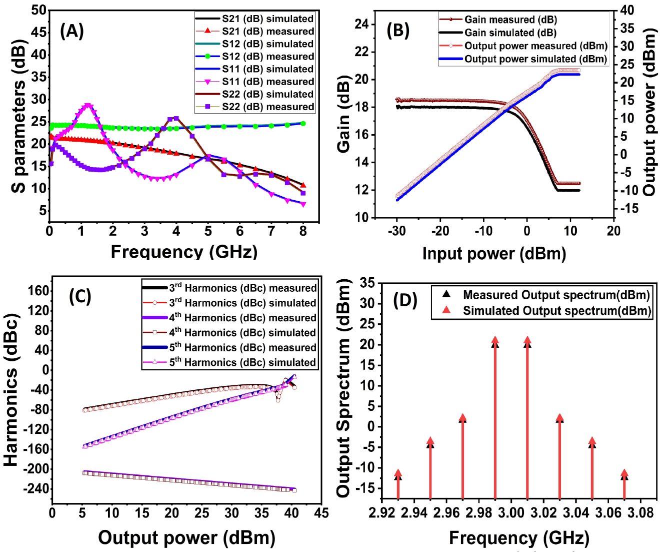

Fig. 3 (A) PA Measured and simulated result of S-parameters (B) of Gain and Output power (C) of third, fourth, and fifth order harmonics (D) of Output spectrum for two-tone measurement.

22.90 dBm respectively. Figure 4 shows the AM-AM and AM-PM plots for measured and simulated results of PA.

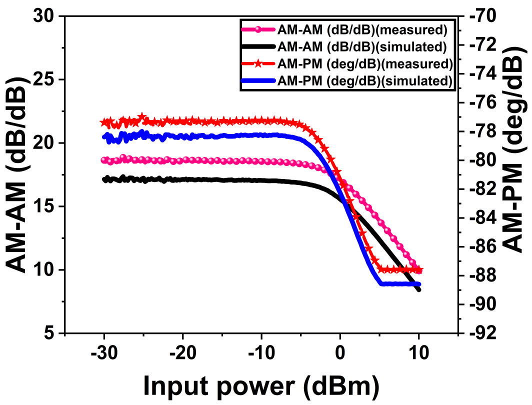

Fig. 4 Measured and simulated results of AM-AM and AM-PM vs input power.

$$\text{NMSE} = \frac{\sum_{i=1}^{N}\left(\text{Y}_{\text{measured}} - \text{Y}_{\text{simulated}}\right)^2}{\sum_{i=1}^{N}\left(\text{Y}_{\text{measured}}\right)^2} \quad (2)$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}\left(\text{Y}_{\text{measured}} - \text{Y}_{\text{simulated}}\right)^2}{\text{N}}} \quad (3)$$

$$\text{MAE} = \frac{\sum_{i=1}^{N}\left(\text{Y}_{\text{measured}} - \text{Y}_{\text{simulated}}\right)}{\text{N}} \quad (4)$$

It is observed that the simulated results of the S-parameter and large signal analysis of PA are similar to the measured results with some magnitude variations (in dB) which can be calculated as an error. This error shows the deviation of the simulated value from the measured value. The performance analysis of relative error between measured and simulated results of different parameters can be performed by calculating the error matrices such as Normalized mean square error (NMSE), Root mean square error (RMSE), and Mean absolute error (MAE). NMSE is defined as the ratio of summation of square of the difference between the $Y_{measured}$ (measured) and $Y_{simulated}$ (simulated) data and summation of square of $Y_{measured}$ (measured) data for N (number of residuals) as given in Eq. 2. It is generally used to measure the normalized error between measured and simulated data. From Eq. 3, RMSE is defined as the square root of the mean square error for N residuals. It is used to measure the standard deviation between the simulated and measured data. From Eq. 4, MAE can be defined as the average of the squared difference between the measured and simulated data. It is used to measure the variance of N residuals.

Table 1 shows the comparative summary of relative error performance for different simulated and measured parameters. The value of N for S11, S12, S21, S22, and ACP is 39. For gain, pout and 1 dB compression point, N = 201 and for 3^{rd} harmonics, 4^{th} harmonics, and 5^{th} harmonics, N = 106. It can be seen that the RMSE value for ACP, i.e. 0.11 is less as compared to other parameters. The value of MAE, i.e. 0.00249 is less for gain, and the value of NMSE, i.e. 0.0000559 is less for S12 as compared to other parameters. The overall performance of NMSE is better compared to the other 2 error matrices. It is due to the existence of less value of deviation between measured and simulated results.

5 Conclusions

In this paper, the behavioral model of the power amplifier is utilized for verifying the nonlinear characteristics of a power amplifier. The measured S-parameters and large signal parameters are imported into S2P and S2D model setup in respective file formats in order to perform small signal and large signal simulations. Then, the obtained simulated results are compared with the measured results to verify the importance of behavioral model in the characterization of the silicon-based power amplifier. The novelty of the proposed work is that instead of making complex circuit design, the analysis of measured data through simulation of PA behavioral models can be easily performed. The error occurring between measured and simulated results for different parameters has been accurately estimated. Among 3 error matrices, NMSE shows the lower value of deviation. The calculated value of NMSE (in %) for S11, S12, S21,

Table 1 Comparison of state of the art PA

Parameter	Measured	Simulated	NMSE	RMSE	MAE
S11 (dB)	-15.68	-15.86	8.31E-05	0.18	0.00415
S12 (dB)	-23.56	-23.74	5.59E-05	0.16	0.00452
S21 (dB)	21.9	21.72	8.60E-05	0.18	0.00462
S22 (dB)	-15.61	-15.79	1.10E-04	0.17	0.00442
Gain (dB)	17.01736	16.51736	8.44E-04	0.5	0.00249
Pout (dBm)	17.43309	16.23309	0.00814	1.2	0.00597
1 dB Compression point (dBm)	24.4	23.3	0.00926	1.1	0.0067
ACP (dBc)	-65.8	-66.9	0.00713	0.11	0.00575
3^{rd} Harmonics (dBc)	-78.6003	-81.1003	0.00225	2.5	0.02358
4^{th} Harmonics (dBc)	-205.396	-207.896	1.22E-04	2.4	0.02158
5^{th} Harmoinics (dBc)	-152.397	-154.897	7.04E-04	2.5	0.02458

S22, gain, pout, 1 dB compression point, ACP, 3^{rd} harmonics, 4^{th} harmonics, and 5^{th} harmonics are 0.0083, 0.0055, 0.0086, 0.011, 0.0844, 0.814, 0.926, 0.71, 0.22, 0.012 and 0.070 respectively. For future extension of this work, instead of using circuit-level simulation, a model-based setup can be utilized for the design and characterization of the power amplifier. After implementation of the model-based setup of PA, accuracy can be greatly improved with a low value of error and performance analysis becoming fast. This work can be utilized to determine the influence of the driver amplifier properties on the power amplifier measurements via simulation.

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Author's Contributions

Shubhankar Majumdar conceived, conceptualized, and supervised the study. Gaurav Bhargava performed the experiments and drafted the manuscript. Farid Medjdoub conceptualized, reviewed, and helped to improve the structure of the manuscript. All the authors commented on the results, provided ideas for the study, and reviewed the manuscript.

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Data Availability

The data may be available as per the requirement of the journal editors.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Consent for Publication

Followed as per the journal's requirement. However, it will not be published as an open-access paper after acceptance.

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