LETTER

Simplified extraction method for broadband power amplifier’s behavioral model

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Abstract The fundamental active load-pull behavioral model, K-parameter, can be used to model the power amplifier (PA) quickly and accurately. When extracting the K-parameter model of a PA, both forward and reverse excitation signals are used in the same time for the PA to establish the large-signal operating point (LSOP). Because of system impedance mismatch and limited isolation of the couplers, the recorded signal is the product of the superposition of forward and reverse excitation vectors. To solve this problem, this paper proposes a data processing method to recover the true forward and reverse excitations on the PA’s ports, while introduces an extraction setup for broadband PA. Finally, a 2-6 GHz 3W PA is used for validation of proposed extraction method.

key words: Broadband power amplifier, behavioral model, extraction method, active load-pull, nonlinear.

Classification: Microwave and millimeter-wave devices, circuits, and modules

1. Introduction

When designing a circuit, electronic design automation (EDA) tools can effectively help engineers predict circuit performance and reduce debugging effort. The accurate simulation by EDA tools is actually based on accurate models [1]. Due to the strong nonlinearity generated by PA, the system performance will be greatly affected, PA is the key and difficult point of modeling.

When performing system simulation, it is only required that PA model can respond to external stimuli without knowing the internal characteristics of the PA, so behavioral models are often used to characterize PAs [2]. The frequency domain models based on poly-harmonic distortion (PHD) theory [3] can directly perform S-parameter simulation for small signals, harmonic balance (HB) simulation for large signals, and envelope simulation in EDA tool [4], which has attracted a lot of attention. The X-parameter [5],[6], Cardiff model[7]-[10], and QPHD model[11]-[14], etc. based on PHD theory have been able to characterize amplifiers more comprehensively and obtain highly accurate simulation results. However, while these behavioral models improve accuracy, the requirements for measurement platforms are becoming higher [15].

For broadband PAs, if X-parameter is used for characterization, a load-pull system needs to be used at the output to consider load mismatch [16],[17], and a driver PA that covers three times the bandwidth of the DUT needs to be used. If Cardiff model is used, a four-port traveling wave measurement system and additional load-pull equipment are required [18]. No matter for X-parameter or Cardiff model, the measurement systems are complex and the cost is high, making it difficult to apply them to engineering modeling on a large scale.

A simplified active load-pull behavioral model, K-parameter, is proposed in [19], which can be used for amplifier modeling. As no isolator or triplexer is used in the measurement, K-parameter is suitable for modeling broadband PAs. However, the forward and reverse excitations work at the same time during model extraction, their signals will overlap at the DUT’s port. For this problem, the traditional solution is to recover the two excitation signals through special tests and vector operations, and then record the responses under different excitations for model extraction. This paper proposes a new setup for broadband PA measurement and a new data processing method based on the characteristics of K-parameter extraction. This method can skip the step of testing the excitation signal, and can obtain accurate excitation signals through a set of tests, while extracting the behavioral model. Due to the simple extraction setup, short test time, and high model accuracy of the proposed method, the proposed method is suitable for the extraction of the behavioral models of broadband amplifiers in practical applications.

2. Actual signals recovery at the ports of DUT

K-parameter can consider the influence between the cross-frequency [20] terms of the input and output products of the DUT, so that it can characterize the nonlinear spectral characteristics of the PA. In order to measure these cross-frequency terms, the hardware test platform must have corresponding measurement capabilities. In order to get the amplitude and phase information of incident and reflected waves, nonlinear network analyzer (NVNA) [21] can be...
used. Directional couplers are employed to collect the signals from main path of measurement. The signals recorded by the couplers are not the actual incident and reflected waves at the DUT ports, but include various errors of the test system, such as tracking response error, mismatch error, and leakage error. The vector calibration technology can be used to extract various error terms of the vector network analyzer and restore the ratios between the reflected and incident waves at the test ports, that is, the S-parameter [22]. And after the calibration of power and phase [23], the amplitude and phase of each incident and reflected waves can be accurately calculated.

Generally, the process of using a vector network analyzer (VNA) for S-parameter measurement is: when one port is excited, the remaining ports are connected to the matching loads, and the amplitude and phase of the signal obtained by each receiver are recorded at the same time, and the error terms determined during vector calibration are used to recover the actual S-parameter [24]. Fig. 1 shows the signals obtained by the four receivers when port 1 uses signal $a_{1,1}$ for excitation. Two superscripts 1 in the reflected waves $b_{1,h}^1$ and $b_{2,h}^1$ indicate that the reflected waves are caused by the excitation at port 1. At the same time, due to the impedance mismatch reflections and the directivity of the coupler, a reverse incident wave $L_{2,1}^r$ will be generated at port 2. However, during S-parameter calibration, there is no corresponding test item, although $L_{2,1}^r$ exists, it is not recorded.

When signal $a_{2,1}$ is used for excitation at port 2, the reflected wave $b_{1,h}^2$ at port 1, the reflected wave $b_{2,h}^2$ at port 2, and the forward incident wave $L_{1,1}^r$ at port 1 can be obtained, as Fig. 2 shows. Similarly, $L_{1,1}^r$ is not considered in S-parameter calibration.

When the DUT’s port 1 performs large forward signal excitation in K-parameter extraction, port 2 also performs reverse signal excitation. That is, the signal obtained by each receiver at this time is the response of the DUT at the LSOP determined by the amplitudes of port 1 and port 2 [25]. The reflected waves $b_{1,h}^1$ and $b_{2,h}^2$ recorded are the reflected signals when two signals are excited at the same time; while the incident wave recorded at port 1 is the vector composition of the excitation signal $a_{1,1}$ of port 1 and $L_{1,1}^r$ generated by port 2; the incident wave recorded at port 2 is the vector composition of the excitation signal $a_{2,1}$ of port 2 and $L_{2,1}^r$ generated by port 1, as shown in Fig. 3. It is worth noting that the values of $L_{1,1}^r$ and $L_{2,1}^r$ are not the same. The reason is that the LSOP when recording $L_{1,1}^r$ is only determined by $a_{1,1}$, but the LSOP when recording $L_{2,1}^r$ is jointly determined by $a_{1,1}$ and $a_{2,1}$, that is, the working status of the DUT at the two moments are different. Similarly, the values of $L_{2,1}^r$ and $L_{2,1}^r$ are also different.

A K-parameter extraction platform is established in simulation tool to explain the signals received by NVNA, as shown in Fig. 4. The DUT is a PA operating at 2-6 GHz with a maximum output power of 35.6 dBm and a gain greater than 30 dB. The measured S-parameter of two back-to-back connected couplers Narda 4226-20 [26] is used to collect the incident and reflected waves. The output power of source 1 is swept from -30 dBm to 10 dBm in step of 5 dBm, while the phase of source 1 is kept constant. The dynamic $a_{2,1}$ amplitude sweeping method in [19] is used to determine the amplitude of source 2 according to the power of incident signal in port 1, and at each step source 2 is swept for 12 phases. The platform has been calibrated, and the incident and reflected waves at the ports of the DUT can be recovered.

Observing the incident wave recorded at port 2 in Fig. 5, it is found that its amplitude and phase changes drastically. The reason is that the amplitude of the forward excitation signal is amplified many times by the PA, so the amplitude
of the reverse excitation $L_{2,1}$ is large, and therefore, the effect becomes greater when it is superimposed with $a_{2,1}$.

According to the definition of K-parameter in [19], each $K_{a,b,m}$ coefficient corresponds to the fixed amplitudes of $a_{1,1}$ and $a_{2,1}$. The incident waves at port 1 and port 2 obtained after the calibration are a product of vector composition, and they do not meet the extraction requirements of K-parameter. It is necessary to recover the amplitude of the actual forward excitation signal $a_{1,1}$ and the amplitude of the reverse excitation signal $a_{2,1}$.

For signal composition, the modeling method of X-parameter is to measure the response of the signal by three times of signal excitation, and then calculate three coefficients of $X^0$, $X^6$, and $X^7$ [27],[28]. In the measurement process, due to the small amplitude of the extraction signal, there may be some errors in calculating the $X^0$ and $X^7$. Generally, 4 extraction signal excitations are used to make the phase evenly distributed in 360°, and then the data regression algorithm is used to calculate the $X^0$ and $X^7$ to improve the accuracy.

Unlike X-parameter, K-parameter does not directly calculate the model coefficients through vectors, but instead fixes the amplitude of the reverse excitation signal and uniformly sweeps its phase to obtain a set of incident and reflected wave signals. This set of recorded incident wave signals can also be used to distinguish between the incident wave caused by forward signal excitation and the incident wave caused by reverse signal excitation.

When the amplitudes of $a_{1,1}$ and $a_{2,1}$ are fixed, the phase of $a_{2,1}$ is swept from 0° to (360-360/N) °, a total of N points. At this time, the incident signal received by port 2 can be expressed by:

$$
\begin{bmatrix}
    a_{2,1,1} \\
    a_{2,1,2} \\
    \vdots \\
    a_{2,1,N}
\end{bmatrix} =
\begin{bmatrix}
    1 & 1 & e^{2\pi j/N} & \cdots & e^{(N-1)2\pi j/N} \\
    \end{bmatrix} \begin{bmatrix}
    L_{2,1} \\
    \end{bmatrix}
$$

where $a_{2,1M}$ is the fundamental forward excitation signal of port 2 obtained by the calibrated receiver, and the initial amplitudes and phases of $L_{2,1}$ and $a_{2,1}$ are expressed as matrix $A$; and the $N$ changeable phases of $a_{2,1}$ and the fixed $L_{2,1}$ are expressed as matrix $E$.

Since the number of rows of matrix $E$ is greater than the number of unknowns in matrix $A$, the least square method can be used to solve the unknown matrix $A$, as shown in Eq. (2), where $H$ represents the Hermitian transpose of the matrix.

$$
[A] = \left[ \left[ E^H \right] \left[ E \right] \right]^{-1} \left[ E^H \right] \left[ a_s \right]
$$

At this time, the reverse incident wave $L_{2,1}$ and the reverse excitation signal $a_{2,1}$ can be separated. The same signal processing method is used to recover the $a_{1,1}$ excitation at the port 1 and the forward incident wave $L_{1,1}$ caused by the reverse excitation.

For the simulation results, the proposed signal processing method is used for data recovering. When the output power of the forward excitation source is 10 dBm, the dynamic $a_{2,1}$ sweeping method is used to determine the amplitude of the reverse excitation signal. Table 1 compares the recovered forward excitation $a_{1,1}$ and the forward incident wave $L_{1,1}$ caused by the reverse excitation using the incident signal of port 1, as well as the recovery of reverse excitation $a_{2,1}$ and the reverse incident wave $L_{2,1}$ caused by the forward excitation using the incident signal of port 2. It can be seen that the amplitude and phase of $a_{1,1}$ recovered are very stable. Due to the internal resistance of the signal source and the insertion loss of test system, the amplitude of the recovered $a_{2,1}$ is about 0.485 times that of the reverse excitation source. It is worth noting that the phase change of $L_{1,1}$ recovered has some fluctuations, and the amplitude of $L_{2,1}$ gradually decreases. This is because the DUT works in strong non-linear region and reverse isolation is changing. While the amplitude of the reverse excitation signal increases, the LSOP of the amplifier changes, resulting in a gradual reduction of the output power and a decrease in the amplitude of $L_{2,1}$.

### Table 1 The recovered incident signals when port 1’s excitation power is fixed to 10dBm.

<table>
<thead>
<tr>
<th>Amplitude of reverse excitation</th>
<th>Forward excitation signal</th>
<th>Forward excitation introduced by reverse excitation</th>
<th>Reverse excitation signal</th>
<th>Reverse excitation introduced by forward excitation $a_{2,1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>excitation source (W/mm²)</td>
<td>(W/mm²)</td>
<td>(W/mm²)</td>
<td>(W/mm²)</td>
<td>(W/mm²)</td>
</tr>
<tr>
<td>1.70</td>
<td>0.968/123.8</td>
<td>3.62E-5/89.5</td>
<td>0.83/147.0</td>
<td>0.63/280.2</td>
</tr>
<tr>
<td>5.11</td>
<td>0.968/123.8</td>
<td>1.11E-4/90.8</td>
<td>2.48/147.0</td>
<td>0.62/880.3</td>
</tr>
<tr>
<td>8.51</td>
<td>0.968/123.8</td>
<td>3.43E-3/98.7</td>
<td>4.13/147.1</td>
<td>0.61/80.4</td>
</tr>
<tr>
<td>11.91</td>
<td>0.968/123.8</td>
<td>5.35E-2/99.2</td>
<td>5.78/147.2</td>
<td>0.59/80.6</td>
</tr>
<tr>
<td>15.32</td>
<td>0.968/123.8</td>
<td>6.13E-1/97.1</td>
<td>7.42/147.2</td>
<td>0.57/80.8</td>
</tr>
<tr>
<td>18.72</td>
<td>0.968/123.8</td>
<td>6.85E-1/96.1</td>
<td>9.07/147.2</td>
<td>0.55/81.1</td>
</tr>
<tr>
<td>22.13</td>
<td>0.968/123.8</td>
<td>8.41E-1/94.9</td>
<td>10.7/147.3</td>
<td>0.52/81.3</td>
</tr>
<tr>
<td>25.53</td>
<td>0.968/123.8</td>
<td>1.06E-0/93.7</td>
<td>12.4/147.3</td>
<td>0.49/81.4</td>
</tr>
</tbody>
</table>

Comparing the recovered reverse excitation signal $a_{2,1}$ with the recorded incident wave signal of port 2 in Fig.6, it
can be found that after data processing, the reverse excitation signal \( L_{2,1} \) introduced by the forward excitation in the overlapping signal can be eliminated.

4. K-parameter extraction and signal processing

In measurement, the diagram of K-parameter extraction platform is shown in Fig. 7. The DUT is a GaN-based PA that operates at 2-6 GHz and has an output power of 35 dBm. Keysight’s NVNA N5247A is used to measure the DUT and record the experimental data. \( R_1 \) and \( R_2 \) are the receivers for incident waves at input and output ports, while \( R_A \) and \( R_C \) are the receivers for scattered waves. The external forward 2-6 GHz driver amplifier can provide an output of 25 dBm, and the PA of MTPA0206-50 [29] with output power of 50 W and frequency of 2-6 GHz is used in the reverse path to amplify the reverse incident wave. As the input signal is small, internal couplers of NVNA is used to collect the incident and reflected waves. At the output of the DUT, two Narda couplers [26] are used for signal collecting. The attenuators in the coupling loop are used to ensure that the power of the signals does not exceed -20 dBm, to make sure the receivers are worked in linear region. An attenuator of 10 dB and 100 W [30] is connected to the output of the DUT to protect the reverse driver PA and serve as a matched load for the output signal of the DUT.

As the test object of K-parameter is a matched PA or power module, its output voltage standing wave ratio (VSWR) is generally less than 3, that is, \( \Gamma_{2,1} \leq 0.5 \). As the output power of the DUT is 35 dBm, the power of the reverse driver amplifier should be 30 dBm [31]. Considering 10 dB attenuation of the attenuator and about 1 dB insertion loss of the coupler and connector, the output of the reverse drive amplifier should be greater than 41 dBm. As the reverse driver PA output power is 47 dBm, it can fall back by 6 dB to generate output power, and it can be considered that its harmonics are not big enough to affect the test.

The measurement settings for the K-parameter extraction of the 2-6 GHz PA are shown in Fig 8. In addition to the main instruments in Fig. 7, an electronic calibration unit (ECal) [32] is used for vector calibration, a power meter is used for power calibration, and a comb spectrum generators are used for phase calibration.

To validate the proposed extraction method, the output power of signal source 2 is kept constant, and the power of input signal source 1 is swept from -20 dBm to 5 dBm to excite the DUT. This research uses different coupler products (Narda 4226-20 and Narda 27000-40 [33]) to study the feasibility of the proposed method under different structures of the measurement system. In Fig. 9, comparison is conducted on the amplitudes of the two sets of recovered reverse excitation signals and the amplitudes of the two sets of reverse incident waves introduced by forward excitation. As the directivity of 27000-40 is worse, the amplitude of the reverse incident wave signal caused by forward excitation is larger. However, when the proposed method is used for data processing, the amplitudes of the two sets of recovered reverse incident wave signals are very stable. It can be seen that for different K-parameter measurement architectures, as
long as calibrations and proposed method are performed, the actual incident signals on the reference plane of the DUT are recovered.

Then the set of recorded incident wave signals, the recovered \( a_{1,1}, a_{2,1} \) and the recorded reflected signals \( b_{1,0} \) and \( b_{2,0} \) are used to conduct K-parameter extraction.

5. Model verification

Using the proposed extraction method, the K-parameter of the 2-6 GHz broadband PA with 35 dBm output can be extracted. While extracting the K-parameters, the voltages and currents at the input and output ports of the DUT are recorded using NVNA and output as mdf file. This file is imported to simulation tool and compared with the simulation results of extracted K-parameter using HB simulator. The comparison of the output fundamental, second and third harmonic results between measurement and K-parameter simulation is shown in the Fig. 10. And the output power and phase of the fundamental and harmonics of the extracted K-parameter model are in good agreement with the measurement results.

As shown in Fig. 11, when the input frequency is 3 GHz and the input power is swept from -30 dBm to 14 dBm, comparison is conducted on the simulation and measurement results of the fundamental, second and third harmonic output power. The coincidence of the fundamental wave is very high in the entire input power range; when the output power of the PA is lower than -60 dBm, the simulation and measured results of the second and third harmonics are slightly different. This is because there are 6 variables in the matrix of \( K_{n,h,m} \), and there are only 8 phases in the swept \( a_{2,1} \), which results in a larger error in extracting the model for small signal excitation. By increasing the number of phase states during model extraction, the accuracy of the K-parameter for small signal response terms can be improved.

Quantitative analysis is performed for the load-pull capability of K-parameter. The absolute fundamental wave error of K-parameter is defined as:

\[
error_{fund} = \left| dBm(V_{out\_fund}) - dBm(V_{out\_fund,K}) \right|
\]

where, \( V_{out\_fund} \) and \( V_{out\_fund,K} \) are the fundamental signals of measured and simulated output.

When the input power is 10 dBm at 3 GHz, the amplitude of the reflection coefficient of the impedance tuner ranges from 0 to 0.7 with an interval of 0.1; the sweeping phase ranges from 0° to 345° with an interval of 15°. The fundamental wave error is plotted on a circle chart as shown in Fig. 12. When the load reflection coefficient is less than 0.5, the fundamental amplitude error of the K-parameter is basically less than 0.2 dB, except for some regions with reflection coefficient phases of 15° to 95°, which can meet the requirements for engineering.

![Fig. 10](image1.jpg) Comparison of measurement and behavioral model simulation results of DUT’s output power (a) and output phase (b) when input power is 10 dBm.

![Fig. 11](image2.jpg) Comparison of measurement and behavioral model simulation results of DUT’s output power when input power is swept

![Fig. 12](image3.jpg) The fundamental wave error when input power is 10 dBm at 3 GHz.
5. Conclusion

According to the characteristics of K-parameter extraction flow, a simplified extraction method is proposed, which can recover the incident signals under large-signal excitation without recording the forward and reverse excitation signals separately, thereby reducing the test time. The test results show that the extracted K-parameters can not only characterize the broadband nonlinearity, but also characterize the load-pull response of the DUT. The proposed method can be used to extract K-parameter of broadband PA at low cost and in a fast manner. And the proposed data processing method can be also used for other behavioral models which use forward and reversed excitation signals simultaneously.

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