Large-signal modeling method for power FETs and diodes*

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Abstract: Under a large signal drive level, a frequency domain black box model of the nonlinear scattering function is introduced into power FETs and diodes. A time domain measurement system and a calibration method based on a digital oscilloscope are designed to extract the nonlinear scattering function of semiconductor devices. The extracted models can reflect the real electrical performance of semiconductor devices and propose a new large-signal model to the design of microwave semiconductor circuits.

Key words: large signal model; extraction method; nonlinear scattering function; semiconductor devices

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1. Introduction

With the wide use of microwave circuits in electronic systems, microwave semiconductor devices and integrated circuits have been rapidly developed in recent years. Microwave semiconductor device computer aided design (CAD) plays an important role in the reduction of design cycles and cost, and for the improvement of the product's performance. The accuracy of the model is the key factor in the design of a microwave circuit.

The former modeling methods[1] mainly include: (1) Models based on a component's physical structure, geometric size and physics equation model, which have the advantage of a high precision but difficult to adapt with the CAD software. (2) Large-signal models based on measurements, which are unrelated to the structure of the devices under test (DUT) and have a good accuracy. They have the drawback of needing large amounts of measurement data and errors coming from the process of measurement and interpolation. (3) Nonlinear empirical models based on large signal equivalent circuits, which are the core of commercial CAD software. They have a limited accuracy and can be derived only after the device is produced. (4) Large-signal models, which are based on the method of artificial intelligence. They have a high speed and a better accuracy; however, they cannot reflect real physical characteristics of semiconductor devices and also need large amounts of measurement data.

In recent years, based on S-parameters at small signals, a large-signal model of the nonlinear scattering function[2] was introduced and it is a frequency domain black box model for semiconductor devices. A nonlinear network measurement system (NNMS) designed by Maury[3] can get amplitudes and phases of incident and reflected waves of devices under real large-signal, one-tone excitation at the input. The model parameters can be extracted based on a relatively small set of measurements. As the NNMS is complicated in structure and high in cost, time-domain measurement systems based on digital oscilloscopes and a frequency-domain analysis method are applied to measurement results and a corresponding calibration method is introduced to extract the nonlinear scattering function. At the end of this paper, examples of this large-signal model for power FETs and diodes are given.

2. Nonlinear scattering function[4–6]

For two-port networks, the incident and reflected waves of each harmonic appear stimulated by the single-frequency signal. Among them, b_j^l represents the l-th normalized reflected wave of port j, and a_i^m represents the m-th normalized incident wave of port i.

In Fig. 1, two ports and triple frequencies ($i, j = 1, 2; m = 1, 2, 3$) are considered. The linear equation (1) of incident and reflected waves of each port can be deduced, and a similar definition can be extended to a multi-port and a high-harmonic. The coefficient S_{ij}^{ml} is called the nonlinear scattering function. It is the plural function of frequency, amplitude, phase and the DC bias. The nonlinear scattering function can change to traditional S-parameters at a small signal. Compared with other large-signal models, a unified model for linear and nonlinear circuits can be built based on this. Its extraction is under a real large signal excitation, and the factor of parasitic parameters and bias conditions are included in the extraction of this

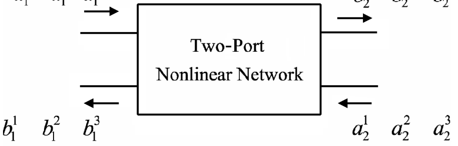

Fig. 1. Definition of nonlinear scattering function to two-port network.

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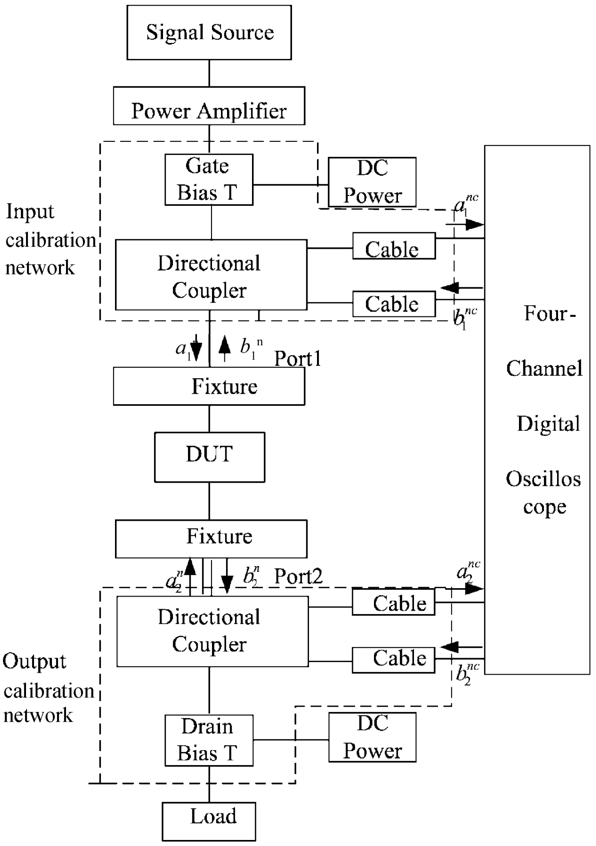

Fig. 2. Extraction system of nonlinear scattering function.

frequency-domain black-box model, which can improve the accuracy.

$$\begin{bmatrix} b_1^1 \\ b_1^2 \\ b_1^3 \\ b_2^1 \\ b_2^2 \\ b_2^3 \end{bmatrix} = \begin{bmatrix} S_{11}^{11} & S_{11}^{12} & S_{11}^{13} & S_{12}^{11} & S_{12}^{12} & S_{12}^{13} \\ S_{11}^{21} & S_{11}^{22} & S_{11}^{23} & S_{12}^{21} & S_{12}^{22} & S_{12}^{23} \\ S_{11}^{31} & S_{11}^{32} & S_{11}^{33} & S_{12}^{31} & S_{12}^{32} & S_{12}^{33} \\ S_{21}^{11} & S_{21}^{12} & S_{21}^{13} & S_{22}^{11} & S_{22}^{12} & S_{22}^{13} \\ S_{21}^{21} & S_{21}^{22} & S_{21}^{23} & S_{22}^{21} & S_{22}^{22} & S_{22}^{23} \\ S_{21}^{31} & S_{21}^{32} & S_{21}^{33} & S_{22}^{31} & S_{22}^{32} & S_{22}^{33} \end{bmatrix} \begin{bmatrix} a_1^1 \\ a_1^2 \\ a_1^3 \\ a_2^1 \\ a_2^2 \\ a_2^3 \end{bmatrix}. \quad (1)$$

It can be concluded that S_{11}^{m1} $(m = 1, 2, 3)$ are fundamental and harmonic reflection coefficients of port 1 caused by the mismatch of devices. S_{21}^{m1} $(m = 1, 2, 3)$ are fundamental and harmonic transmission coefficients from port 1 to port 2. Each scattering function has physical implications itself. To extract the nonlinear scattering function of a DUT, the amplitudes and phases of inflected and reflected waves need to be measured.

3. Time domain extraction system and calibration method of the large-signal model

The measurement and extraction system of the nonlinear scattering function is illustrated in Fig. 2. DPO7254, a four-channel digital oscilloscope, which is the core of the time domain measurement system, has a 10 GHz sampling rate, a 2.5 GHz analog bandwidth and can do the spectrum analysis inside it. With a simple directional coupler in the extraction system, incident and reflected waves can be separated. Because of the imperfect isolation of the directional coupler and errors from bias and cables, some calibration procedures should be adopted.

It can be concluded that the input and output network is isolated, so we can calibrate them respectively. Among them, $a_1^n, b_1^n, a_2^n, b_2^n$ are real incident and reflected waves of the DUT and $a_1^{nc}, b_1^{nc}, a_2^{nc}, b_2^{nc}$ are values measured by an oscilloscope. As the whole system is linear, relations between them can be expressed with the following error model:

$$\begin{bmatrix} a_1^n \\ b_1^n \\ a_2^n \\ b_2^n \end{bmatrix} = k^n \begin{bmatrix} 1 & \beta^n & 0 & 0 \\ \chi^n & \delta^n & 0 & 0 \\ 0 & 0 & \varepsilon^n & \phi^n \\ 0 & 0 & \gamma^n & \eta^n \end{bmatrix} \begin{bmatrix} a_1^{nc} \\ b_1^{nc} \\ a_2^{nc} \\ b_2^{nc} \end{bmatrix}. \quad (2)$$

If we define $k^n = K^n e^{j\varphi_n}$, K^n is the amplitude error coefficient of each frequency signal, and $e^{j\varphi_n}$ is the phase error coefficient. Elements of the matrix above are RF error coefficients. Similar to a classical SOLT calibration, through connecting four calibration standards between two ports, which are short, open, load, and through standards, the RF error coefficients above can be derived. By connecting the power meter and the phase standard, K^n and $e^{j\varphi_n}$ can be derived. With these coefficients, real incident and reflected waves can be calculated through the values measured by the oscilloscope. This calibration model designed can calibrate fundamental and harmonic components measured by an oscilloscope simultaneously. It has been developed as software and combined with control software of the oscilloscope. Real incident and reflected waves of the DUT can be gotten directly from the oscilloscope and the nonlinear scattering function is calculated from them.

4. Modeling method examples of power FETs and diodes[7, 8]

4.1. Examples of power FETs

Three kinds of power FETs, which include MRF281, MRF158, and MRF9030, are adopted as examples to extract the large-signal model. With amplitudes and phases of incident and reflected waves, a large-signal model based on the nonlinear scattering function can be built. Amplitudes of the first column scattering function can be calculated from the measurement results of a Motorola MRF281 MOSFET, with V_{GS} = 4.5 V and V_{DS} = 22 V. The power changes from 5 to 28.5 dBm with a 0.5 dBm interval. Figure 3 shows the amplitude change of the nonlinear scattering function at a frequency of 900 MHz.

4.2. Examples of diodes

For the varactor MA6506 stimulated at port 1, the excitation frequency varies from 500 to 800 MHz with a 20 MHz interval, and the power changes from –5 to 15 dBm with a 0.5 dBm interval. Figure 4 shows the amplitudes of the nonlinear scattering function at 600 MHz.

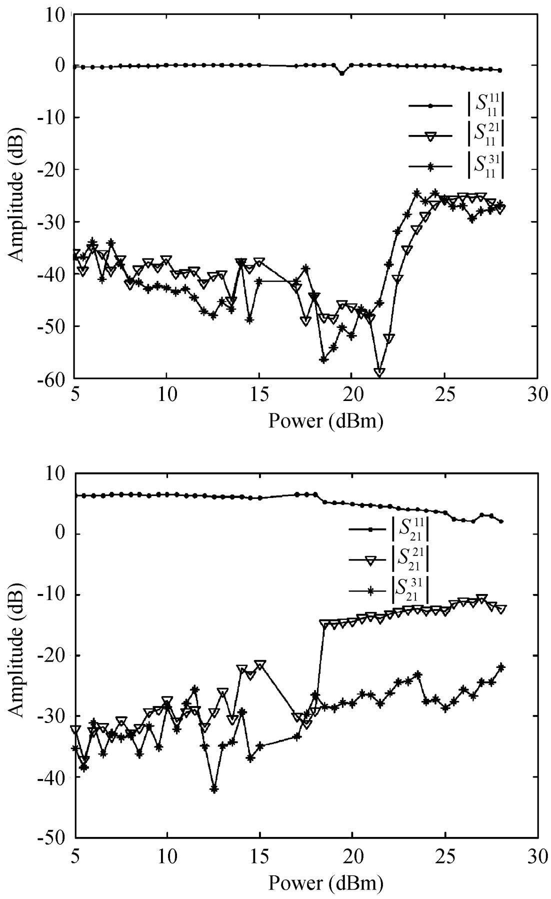

Fig. 3. Nonlinear scattering function of MRF281 at 900 MHz.

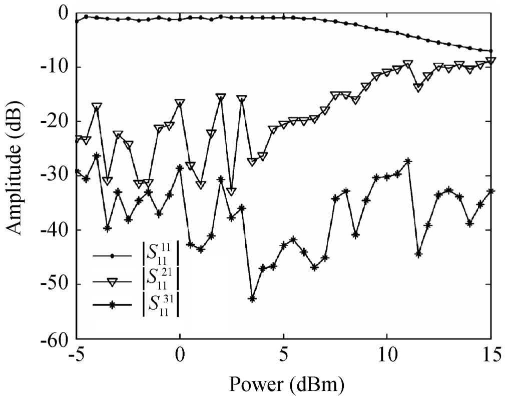

Fig. 4. Nonlinear scattering function of the varactor at 600 MHz.

For the SRD MA4769, the frequency and the power changes of the excitation signal are the same as for the varactor above. Figure 5 shows the time domain waveform of the excitation and the output signal of the SRD at 600 MHz and 16 dBm. It can be seen that reversing SRD releases a steep step, which shows that the output of the diode includes a large amount of harmonic components. Figure 6 shows the amplitudes of the nonlinear scattering function at 600 MHz.

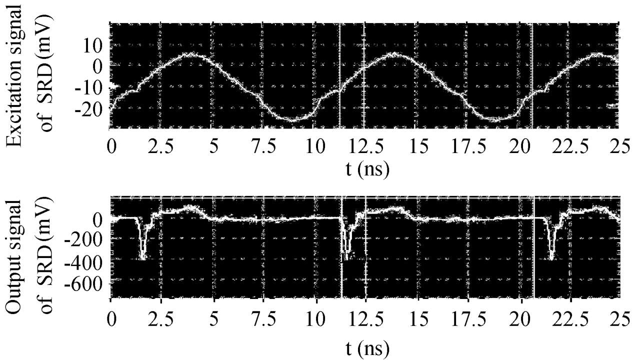

Fig. 5. Time domain waveform of the excitation and the output signal of the SRD at 600 MHz and 16 dBm.

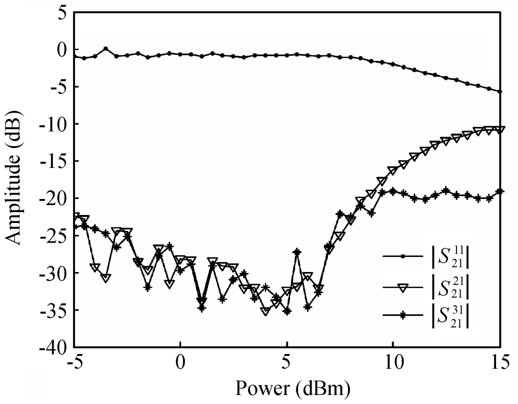

Fig. 6. Nonlinear scattering function of the SRD at 600 MHz.

With the increase of input power, the nonlinear characteristic of the semiconductor devices emerges. The reflection and transmission powers of the fundamental component decreases, but the powers of the second and third harmonic components gradually increase. It can be seen from the change of the scattering function that the amplitudes of the fundamental reflection coefficients reduce and the harmonic reflection coefficients increase. The fundamental transmission coefficients decrease and the harmonic transmission coefficients increase as well. The result agrees with nonlinear characteristics of power FETs and diodes. The extracted nonlinear scattering function can be used to design the input and output matching networks of microwave semiconductor nonlinear circuits; the model has been successfully applied to the design of a diode frequency-doubler[9]. Using traditional nonlinear circuit analysis methods of harmonic balance and volterra series, the nonlinear scattering function of semiconductor devices can be calculated to verify this large-signal model.

5. Conclusions

A frequency domain black box model of a nonlinear scattering function is adopted as a new large-signal model of power FETs and diodes. A time domain extraction system and a new calibration method are used to extract this model and the result reflects the nonlinearity of semiconductor devices following an increase of the input power. The further research will focus on the calibration of the phase, how to build an artificial intelligence model of semiconductor devices based on the nonlinear scattering function, and how to realize a microwave nonlinear circuit CAD using this model.

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