Transient Analysis of Nonlinear Microwave Circuits Using Small-Signal Scattering Parameters

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Abstract - **A transient analysis method for nonlinear microwave circuit analysis is described in this paper. S-parameter microwave circuit theory and measurement-based small-signal scattering parameters of nonlinear devices are used directly to construct the large signal response of the circuits. This consistent modeling and analysis approach retains all the frequency-dependence information of the measured small-signal parameters. The method is applied to predict the large signal performance of a discrete AlGaN/GaN high electron mobility transistor (HEMT), biased in the common source amplifier mode. Reasonable agreement between the simulated and measured results is obtained. This method does not have limitations on the number of input carrier frequencies or the total number of frequencies. It is expected to be a useful and efficient tool in waveform engineering applications.**

I. Introduction

The number of carrier frequencies limits the application of the Harmonic-Balance (HB) method, which has matured as the workhorse for nonlinear microwave circuit analyses [1]. A newly proposed frequency-domain method in [2] allows more accurate description of the frequency dependence than that of the Root model [3]. It can also be applied to strongly nonlinear circuit analysis, where the conventional frequency-domain methods, such as power series and Volterra-series analysis [1], are not appropriate. However, the total number of frequencies that can be considered is still limited.

Microwave circuits intended for telecommunication applications are expected to handle one or more carriers modulated with non-null information signals, i.e., finite bandwidth excitations. The bandwidth issue is more pronounced in CDMA and the emerging ultra-wide-band (UWB) communication systems [4], [5]. Furthermore, waveform engineering for the linearization of power amplifiers in CDMA systems [6], waveform analysis of high-efficiency power amplifiers (such as class F) [7], [8] and UWB systems require accurate transient analysis and simulation methods for nonlinear microwave circuits, which was considered not necessary a decade ago [9]. The broadband nature of those problems makes the available methods difficult to use.

Here we propose a general method for nonlinear circuit transient analysis based on measured small-signal scattering parameters. The method does not suffer from the limitations of the aforementioned approaches. The procedure directly constructs large signal response from small-signal scattering parameters. Without loss of generality, the method is corroborated through the analysis of a discrete AlGaN/GaN HEMT, biased in a common source mode [10] shown in Fig.1 (a).

II. The Frequency-Domain Algorithm

The small-signal s-parameter characterization of FET in Fig. 1(a) is well established, but the large signal characterization and modeling of the FET is not well established in the time and power ranges of interest. So far, not much of the mature and elegant linear microwave circuit theory has been applied to this nonlinear microwave circuit analysis. In fact, small-signal s-parameter characterization of the FET in the full bias and frequency parameter space, in conjunction with the knowledge of the small-signal equivalent circuit model in Fig. 1(b), allows a two-port network representation shown in Fig. 1(c). Notice here the intrinsic transistor s-parameters are bias dependent. The separation of the intrinsic transistor (nonlinear) with the parasitic components (linear) is necessary due to nonlinear voltage re-referencing [11] in the following circuit analysis; otherwise a weak nonlinearity assumption, such as that in Volterra-series analysis [1], would be necessary. The full-space small-signal s-parameters contain all the information needed for large signal modeling, provided that the quasi-static assumption is satisfied [12]. Therefore, the large signal model can be constructed as in Fig. 1(d). In fact, this is the starting point of the modeling methods in [2] and [3], where further assumptions are made for the relevant algorithms. The quasi-static assumption is necessary for all the available data-based nonlinear modeling methods [1]-[2].

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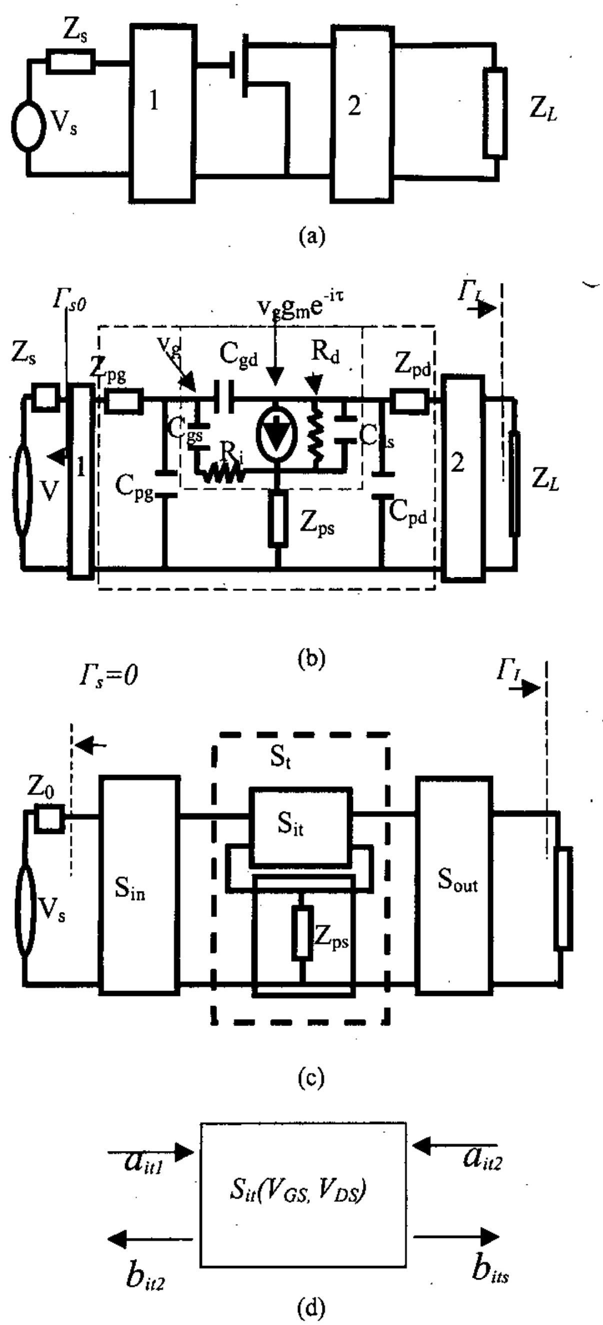


Fig. 1. (a) Schematic of a common source microwave power amplifier. Block 1 is the input network, including the gate bias circuit. Block 2 is the output network, including the drain bias circuit. Z_s is the source impedance, and Z_L is the load. (b) Circuit representation using HEMT equivalent circuit element model. (c) Two-port network representation of the circuit. Z_0 is the reference impedance. S_{in} includes Z_s-Z_0 and the input network in (b), Z_{pg} and C_{pg}. S_{it} is the intrinsic transistor. S_t includes S_{it} and Z_{ps}. (d)

The large signal FET model with intrinsic constitutive relations defined for port characteristics.

Transient analysis needs to calculate the circuit response to an arbitrary input signal, as shown in Fig. 2. We approximate the input signal as the summation of small amplitude step-functions, each with a different time delay as shown in Fig.2. The flow chart of the proposed frequency-domain algorithm is shown in Fig.3.

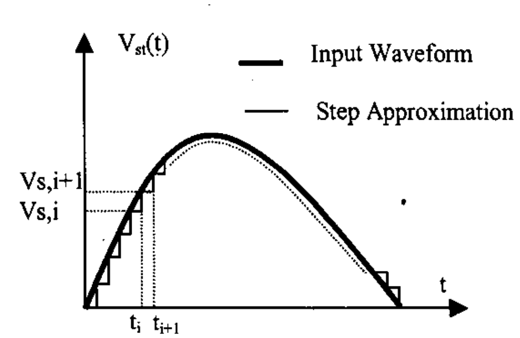


Fig. 2 Approximation of input waveform

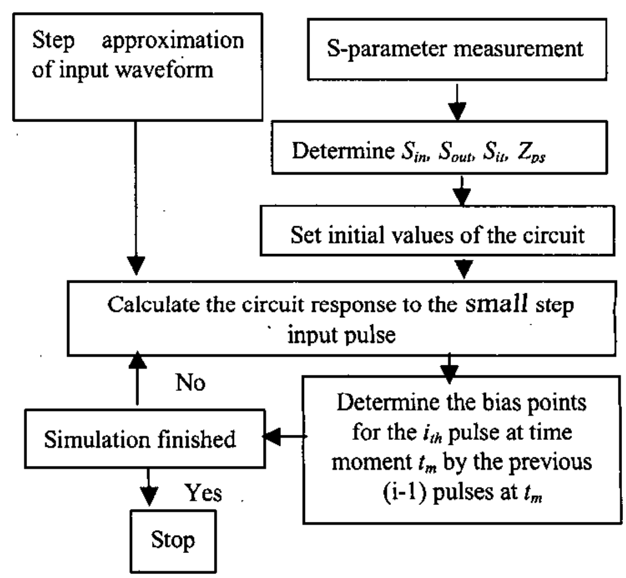


Fig.3. A flow chart of the frequency-domain algorithm.

The i_{th} step function is

$$V_s(t) = \sum_{i=1}^{n} (V_{s,i+1} - V_{s,i}) u(t - t_i) \quad (1)$$

where n is the number of discrete steps. The Fourier transform of the i_{th} step-function is,

$$V_{s,i}(\omega) = (V_{s,i+1} - V_{s,i})(\pi\delta(\omega) + \frac{1}{j\omega})\exp(-j\omega t_i) \quad (2)$$

The response of the circuit to the i_{th} small step input pulse can be found using microwave circuit theory [13] through the signal flow graph in Fig. 4.

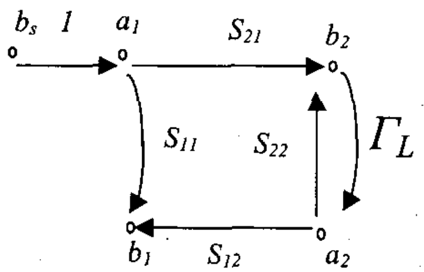


Fig. 4. The signal flow graph of the circuit in Fig. 1(c). Cascading S_{in}, S_t and S_{out} gives the S parameter in this figure

In Fig. 4, we have

$$b_s = \frac{V_{s,i}}{2\sqrt{Z_0}} \quad (3)$$

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} \quad (4)$$

$$a_1 = b_s$$
$$a_2 = b_s \frac{\Gamma_L S_{21}}{1 - \Gamma_L S_{22}}$$
$$b_1 = b_s \frac{S_{11} - \Gamma_L \Delta S}{1 - \Gamma_L S_{22}} \quad (5)$$
$$b_2 = b_s \frac{S_{21}}{1 - \Gamma_L S_{22}}$$
$$\Delta S = S_{11}S_{22} - S_{12}S_{21}$$

With the incident and reflected waves given in equations (3)-(5), the voltages and currents at any given port in circuit Fig.1 (c) can be obtained easily with the help of the scattering parameters of the relevant network. The inverse Fourier transformation gives the voltages and currents at the time moment of interest. The new bias point for the next small step input at the next time moment is then obtained by the summation of all the responses of previous small step inputs at a particular time moment

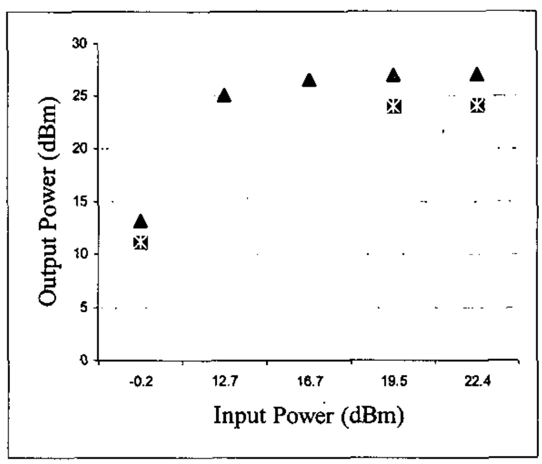
III. SIMULATION ANALYSIS OF A HEMT AMPLIFIER

The proposed method is applied to the simulation analysis of a discrete AlGaN/GaN HEMT, biased in the common source amplifier mode [10]. The small-signal s-parameters are measured using an HP 8510C network analyzer in the parameter space shown in table 1.

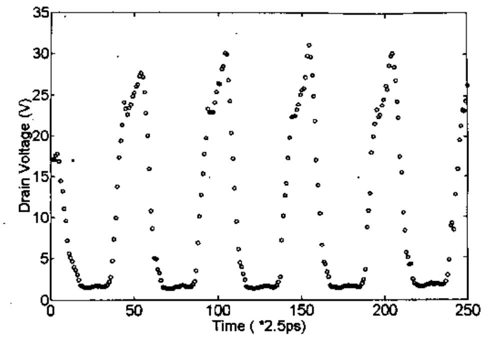
Table 1. Small-signal s-parameter space

	Gate Bias (V)	Drain Bias (V)	Frequency (GHz)
Start Value	-7.5	0	1
Step Size	0.5	3	0.25
Stop Value	2	15	26.5

Linear interpolation and extrapolation methods are used to obtain the small-signal s-parameter data for gate and drain bias points other than the measured ones. No efforts have been made in the frequency domain data extrapolation; it is well known that the extrapolation to lower frequencies does not work well [11]. Fig. 5 (a) shows both the measured and simulated output power. A reasonable agreement is observed. However, the simulated power level at 8GHz is about 3dB lower than the measured data. Fig. 5(b) shows the simulated drain voltage waveform under high input voltage excitations. The drain voltage shape is far from a sine wave. It is also not smooth. The discrepancy between the measured and simulated output power as well as the rough voltage waveform may be partly attributed to the sparsity of the measured data space listed in table 1. The data extrapolation process may also account for part of the discrepancies. The lack of s-parameter data in lower frequency affects the accuracy of the simulation.



(a)



(b)

Fig. 5 Measured and simulated results. (a) Output power. The squares represent the simulated points, and the triangles are measured points; (b) Simulated output voltage waveforms.

IV. Discussions and Conclusions

The division of the input waveform into the finite number of pulse steps also contributed to the deviation in the simulation shown above. Measured data space larger than that shown in table 1 is expected to bridge the simulation closer to the experiment. The accuracy of the method depends on the accuracy of the measured scattering parameter data as well. Further investigations are necessary to quantify the limiting factors, especially the applicable frequency range, though no measured frequency information is lost [14].

The input pulse waveform can also be approximated as the summation of narrow square functions, each with a different time delay. An algorithm similar to that in Fig. 3 may be developed for the relevant simulation analysis [15].

In conclusion, we presented a small-signal s-parameter based method for nonlinear microwave circuit analysis. Its transient nature makes it a promising method for waveform engineering applications, including UWB system analysis. It is also applicable to high-speed interconnect transient analysis [15]. The direct application of small s-parameter data makes the method consistent with small-signal modeling and analysis practices. The small-signal s-parameter circuit analysis methods are, therefore, naturally used as the core for the large signal analysis, not by using brute force as in the present large-signal s-parameter efforts [16].

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