Electromagnetic Effects Analysis at System-level Considering Nonlinear Components

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Abstract

A fast frequency domain system-level analysis method of electromagnetic effects on an electronic system containing nonlinear components is presented. The nonlinear behavior of components is represented by nonlinear scattering parameters based on a black-box model, and then a modeling approach for electromagnetic field coupling to microstrip line connected with nonlinear component/module is proposed. The system-level analysis method is experimentally validated by a laboratory system including a simple nonlinear component, which is constituted by the anti-paralleled HSMS-282C Schottky diodes pair welded to a 50Ω microstrip line. The calculated results using the proposed method show good agreements with the measured data.

1. Introduction

The electromagnetic environmental effects attract increasing interests of researchers as more and more wireless communication systems have been developed and applied widely. Researchers begin to pay increasing attentions to electromagnetic compatibility analysis at system level [1, 2]. An electronic system inevitably composes of linear/nonlinear components, cables and apertures, leading to a complicated interaction between electromagnetic wave and the system. Especially the nonlinear behavior of components may make the interaction even more complicated. Although measurements are the necessary approaches for system-level electromagnetic effects analysis, they are costly and time consuming. Full wave analysis has been widely used for electromagnetic effects simulation at component-level or for a certain problem, such as aperture coupling, field-to-transmission line coupling or the effects on semiconductors. However, when a complex system is mentioned, the accurate structure description required and the complicated interaction between the electromagnetic wave and nonlinear components make it very time-consuming and hard to implement the full wave simulation effectively.

Therefore, an appropriate model which fastens the electromagnetic effects analysis at system level considering the nonlinear effects is wanted. In this paper, we present a fast frequency-domain technique that employs the nonlinear scattering parameters (S-parameter) to provide the required information at system level.

2. Modeling of Eleletromagnetic Effects Analysis at system level

The external electromagnetic wave influence an electronic system mainly through three paths, conduction through a receiving antenna, aperture coupling and field coupling to a transmission line (TL). Here we only put emphasis on conduction and field-to-transmission line coupling, because the aperture coupling influence the field distribution inside the enclosure and then influence the system through field-to-TL coupling. Consequently, the system-level electromagnetic effects analysis including two parts, field coupling to transmission line and conduction modeling.

S-parameters based on microwave network provide a fast conduction analysis approach at system level. The response at the ports of each device can be calculated when S-parameters of devices inside the system are given. However, traditional S-parameters represent only the linear behavior of networks. Moreover, the classical field-to-TL coupling theory [3] is usually applied for the transmission line terminated with linear loads. Though nonlinear loads in such a problem have been investigated [4-6], the nonlinear effects transmitted from the output port of a component/module towards the next one never been mentioned, because components are treated as one-port loads in these reports. Therefore,

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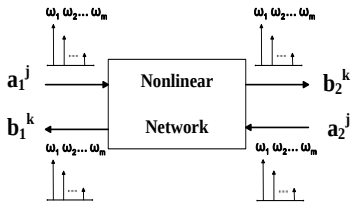
a complete system-level electromagnetic effects analysis can become practical, provided that the models of the nonlinear blocks are given.

Fortunately, nonlinear large-signal scattering-parameters (S_N-parameters), which are based on the black box model in frequency-domain, can be used to describe the nonlinear behavior of components/modules [7]. It is defined as ratios of the reflected and incident wave variables of each port, as shown in Fig. 1. where each element S_{nm}^{kj} in $[S_N]$ can be defined as Eq. (1). Using this $[S_N]$ matrix, the outputs at each port can be easily obtained, and measurement to get this matrix is discussed in [8].



$$\begin{bmatrix} b_1^1 \\ b_1^2 \\ b_1^3 \\ \hline b_2^1 \\ b_2^2 \\ b_2^3 \end{bmatrix} = \left[\begin{array}{ccc|ccc} S_{11}^{11} & S_{11}^{12} & S_{11}^{13} & S_{12}^{11} & S_{12}^{12} & S_{12}^{13} \\ S_{11}^{21} & S_{11}^{22} & S_{11}^{23} & S_{12}^{21} & S_{12}^{22} & S_{12}^{23} \\ S_{11}^{31} & S_{11}^{32} & S_{11}^{33} & S_{12}^{31} & S_{12}^{32} & S_{12}^{33} \\ \hline S_{21}^{11} & S_{21}^{12} & S_{21}^{13} & S_{22}^{11} & S_{22}^{12} & S_{22}^{13} \\ S_{21}^{21} & S_{21}^{22} & S_{21}^{23} & S_{22}^{21} & S_{22}^{22} & S_{22}^{23} \\ S_{21}^{31} & S_{21}^{32} & S_{21}^{33} & S_{22}^{31} & S_{22}^{32} & S_{22}^{33} \end{array}\right] \begin{bmatrix} a_1^1 \\ a_1^2 \\ a_1^3 \\ \hline a_2^1 \\ a_2^2 \\ a_2^3 \end{bmatrix}$$

Fig.1 (a) Diagram and (b) NS-parameters definition of a nonlinear two-port network.

$$S_{nm}^{kj} = \frac{b_n^k}{a_m^j} \begin{cases} a_x^y = 0 \text{ for } x \neq m \\ a_x^y = 0 \text{ for all } x = m \text{ \& all } y \neq j \end{cases} \tag{1}$$

When a device with nonlinear behavior is connected with TL, the nonlinear effects should be considered in the field coupling to the line. This nonlinear effects can be equivalent as an impedance which varies as the power injected to the component/module changes. This equivalent impedance Z_{eff} can be obtained using commercial software ADS or from the measurement. Introducing Z_{eff} into the field coupling to TL equations, we can calculate the power injected into the nonlinear component/module. Note, this is an iterative procedure, since the impedance Z_{eff} varies with the injected power. Once the power into the nonlinear network is known, the output power at each port can be calculated according to $[b] = [S_N][a]$. Even if the nonlinear component/module followed by other linear/nonlinear components/modules, the output power at each port can also be calculated using cascade networks operation [9].

The system-level electromagnetic effects analysis approach can be summarized as the following steps.

1) Understand the electromagnetic energy propagation path in the whole system, and obtain the topology network of the system.
2) Obtain the S-parameters/NS-parameters and equivalent impedance Z_{eff} of each important component/module by simulation or measurement. (Important here means that the component/module must be taken into consideration for the effects analysis at system level.)
3) Calculate the induced current and voltage on the transmission line due to the electromagnetic field around it, and then get the power P_{in} flowing into the component/module connected with it.
4) Obtain the *S*-parameters of the cascade networks $[S]_{tot}$. and then calculate the P_{out} at each port of the key component.

3. Experimental Results

The validation of the results obtained from the proposed analysis method is supported by experimental data measured on a laboratory system, as shown in Fig.2. A TEM cell is used to generate a relatively uniform electromagnetic field, and a 40mm long 50Ω microstrip line printed on a 1mm thick substrate with relative dielectric constant of ε_r = 2.65 is placed vertically inside the cell. Outside the cell, a simple nonlinear component is connected to it and followed by a low-pass filter (LPF) with cutoff frequency of 3GHz. This nonlinear component consists of anti-paralleled HSMS-282C Schottky diodes pair welded at the center of the conductor strip of a 50Ω microstrip line. The cell is excited by a single tone microwave power source at 2.5GHz, and the output power from the LPF P_{out} as well as the reflected power P_r at port A of the microstrip line are measured using two broadband R&S-FSV signal analyzers respectively.

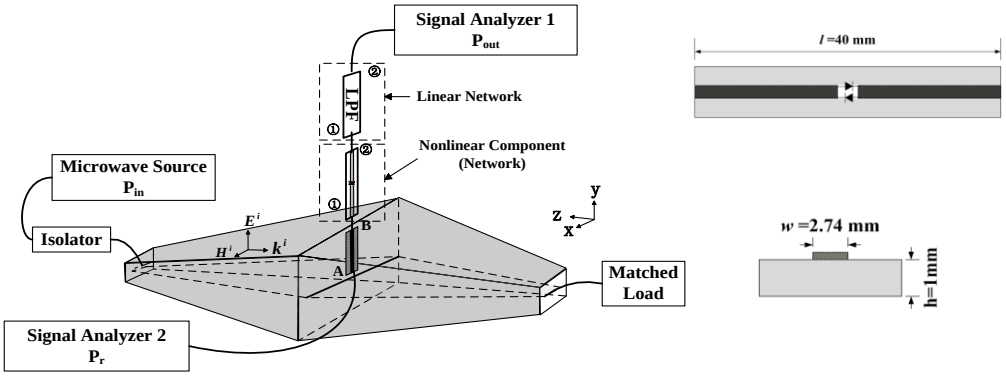
First, parameters in the $[S_N]$ of the nonlinear component is obtained through measurements, and results shown in Fig. 3. Those measured results include fundamental and the third harmonic components, while the second harmonic component cannot be detected because the even harmonic components circulate within the loop formed by the two anti-paralleled diodes. Plots in Fig.3 show that the reflection and transmission of both the fundamental and third harmonic components vary nonlinearly in terms of the input power. Especially, the power of the fundamental component is much larger than that of the third harmonic ones. Since the single tone signal is fed into the component, namely elements in

matrix $[a]$ is zero except for a_1^1, only the necessary elements in $[S_N]$ are obtained. The S-parameters of the LPF $[S_L]$is measured up to 13GHz and results are not shown here due to the paper length limitation. Then the S-parameters of the cascade networks $[S]_{tot}$ can be calculated using the following.

$$[S]_{tot} = [[S_{11NL}] + [S_{12NL}][[G] - [S_{22NL}]]^{-1}[S_{21NL}]] \tag{2a}$$

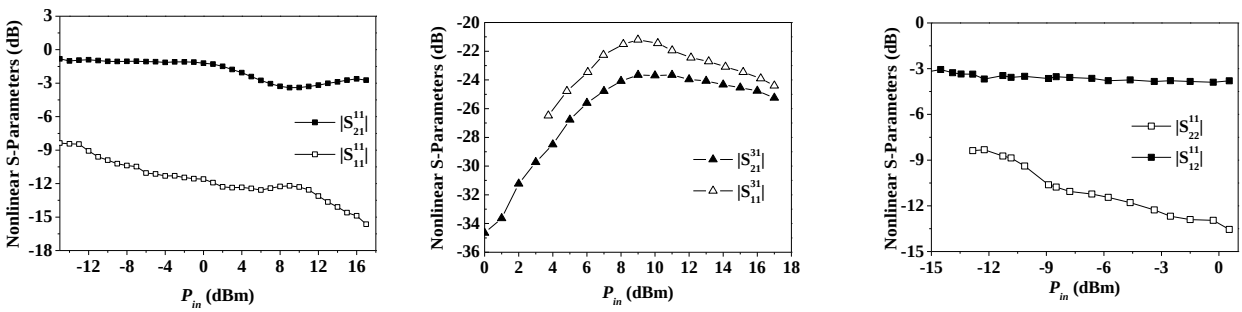
$$[S_{11NL}] = \begin{bmatrix} S_{11N}^{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ S_{11N}^{31} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, [S_{12NL}] = \begin{bmatrix} S_{12N}^{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ S_{12N}^{31} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & S_{21L}^{11} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, [S_{21NL}] = \begin{bmatrix} S_{21N}^{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ S_{21N}^{31} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, [S_{22NL}] = \begin{bmatrix} S_{22N}^{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ S_{22N}^{31} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & S_{11L}^{11} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & S_{11L}^{33} \end{bmatrix} \tag{2b}$$

where S_{11L}^{11}, S_{21L}^{11} represent the S_{11} and S_{21} of the LPF at fundamental frequency 2.5GHz, while S_{11L}^{11} means S_{11} at the third harmonic frequency 7.5GHz. Finally the output power at each port of the cascade network can be predicted according to $[b] = [S]_{tot}[a]$, and results are shown in Fig.4.



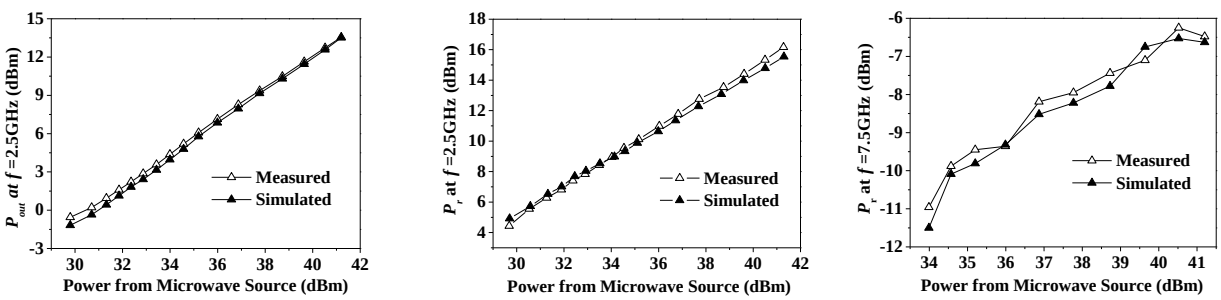
(a) (b)

Fig. 2 (a) Experimental system, (b) nonlinear component used.



(a) $\left|S_{21}^{11}\right|$ 和 $\left|S_{11}^{11}\right|$ (b) $\left|S_{21}^{31}\right|$ 和 $\left|S_{11}^{31}\right|$ (c) $\left|S_{22}^{11}\right|$ 和 $\left|S_{12}^{11}\right|$

Fig. 3 Results of parameters in $[NS]$ of the nonlinear componet



(a) (b) (c)

Fig. 4 Comparison of measured and simulated results, (a) output power of the fundamental wave, (b) the reflected power of the fundamental wave and (c) the reflected power of the third harmonic wave.

As expected, there is only fundamental component can be detected at the port ② of LPF in Fig.4 because the third harmonic component is filtered by LPF. However, both fundamental and the third harmonic component are measured at the port A of the microstrip line, since the signal at this port includes the power reflected from the nonlinear component. The predicted results are in good agreement with the measured ones, which demonstrate the validation of the proposed method.

4. Conclusion

A fast frequency domain system-level analysis method of electromagnetic effects on an electronic system containing nonlinear components is presented here. The proposed method is experimentally validated by a laboratory system including a simple nonlinear component. Results show good agreements between the measured and predicted data. Though nonlinear S-parameters may not represents all the nonlinear behavior of components at present, and maybe not easy to obtain, the proposed method is more practical than full wave analysis for the electromagnetic effects analysis at system level.

6. Acknowledgments

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7. References

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