A Full-wave Analysis of RF Circuit with Active Devices by the FDTD Method Using Scattering Parameters

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I. INTRODUCTION

Recently, for an RF circuit, there is an inexorable trend toward higher frequencies and increased package densities. A design for such circuits encounters the severe problem of dealing with the electromagnetic coupling and undesired radiation. This situation creates a need for a full-wave analysis method. Generally, the FDTD method is applied to analyze various RF circuits. The FDTD method is the most suitable method for this purpose because of its simple and flexible algorithm for numerical solution of Maxwell's equations.

In the analysis of circuits with lumped elements by the FDTD method, lumped elements are treated as subgrid models [1] or lumped elements are modeled by SPICE models [2]. However, in such cases, the FDTD method results in the consumption of considerable computer time. The former case imposes complexity on the software, and the latter case imposes an additional heavy routine, namely an exchange of the data between FDTD and SPICE. Another method converts the S-parameters of the two-port network into Y-parameters, and uses the inverse fast Fourier transform (IFFT) to obtain the time-domain series of the Y-parameters [3]. It is impossible to apply this approach in order to analyze active elements whose characteristics depend on the incident waves, and so the incident waves are unknown.

The purpose of this paper is to propose a new FDTD method using the scattering parameters (S-parameters) of nonlinear active elements in a time domain. This paper demonstrates a simple microstrip circuit with a lumped element network that consists of resistors, capacitors, and inductors. First, S- parameters in a frequency domain of the device are transformed into a time domain using the inverse Fourier transform. Next, the incident waves are calculated from the observed, reflected, and transmitted waves. Because the proposed approach is suitable for the arbitrary incident waves, the incident waves do not have to be calculated in advance on microstrip lines. Finally, RF circuits are simulated by the FDTD method using S-parameters. The real circuits are employed to validate the efficiency and accuracy of the proposed method. S_{11} and S_{21} of an amplifier circuit are calculated, and they both show good agreement with the measured and calculated results.

II. MODELING THE RF CIRCUIT

A linear component in an RF circuit can be considered to be an M-port RF circuit. These ports are connected to microstrip lines. For the sake of conciseness, then following discussion focuses on a two-port RF circuit. Fig. 1 represents a two-port RF circuit ($S_{mn}(f)$) and a microstrip line (MSL), where R (= Z_0) is the terminating impedance. These ports are connected to microstrip lines. S-parameters, extracted from measurement or other simulations, are usually used as characteristic variable in the frequency domain. S-parameters in the frequency domain are transformed into the time domain using the IFFT. S-parameters in the time domain are $S_{mn}(t)$ as shown in Fig. 1.

Once the cell size in the FDTD method is determined, the maximum size of the time step Δt immediately follows from the Courant stability criterion. The time step Δt is bounded by the Courant stability criterion as shown in eq. (1).

$$\Delta t \leq \frac{1}{c \cdot \sqrt{(1/\Delta x)^2 + (1/\Delta y)^2 + (1/\Delta z)^2}} \qquad (1)$$

where c is the propagation velocity and Δx, Δy, and Δz are the minimum cell space in the FDTD grid. Therefore, the time step (Δt) must be reduced below the highest-frequency sampling cycle. Generally, this is not a problem. Because in most calculations the time step size satisfies the Courant stability criterion, the time step is usually very small in the FDTD method. For example, Δt = 1.67[ps] ($\Delta x = \Delta y = \Delta z = 1$[mm]) is very much smaller than 500[ps] (the sampling cycle of 1GHz). Based on the results, S-parameters in a frequency domain are transformed into a time domain using the IFFT.

The voltage sources are V_{xx} as shown in Fig.1. The temporal offset is understood as follows.

First, the incident wave V_{1in} at port 1 is defined as

$$V_{1in}[n] \cong V_{1view}[n-1] - V_{11}[n-1] - V_{12}[n-1] \qquad (2)$$

where t = $n\Delta t$, $V_{1view}[n] = V_{1view}(n\Delta t)$, $V_{11}[n] = V_{11}(n\Delta t)$, $V_{12}[n] = V_{12}(n\Delta t)$, n = 1,2,$\cdots$ (Δt is the time step).

$V_{1view}[n-1]$ and $V_{11}[n-1]$ represent view voltage and the reflection voltage in the time domain at port 1, respectively. $V_{12}[n-1]$ represent the transient voltage in the time domain from port 2 to port 1. V_{1view}, V_{11}, and V_{12} have the same time. Besides, V_{11} and V_{12} are obtained by V_{1in} using S-parameters (S_{11} and S_{12}, respectively).

For the same method, the incident wave V_{2in} at port 2 is defined as

$$V_{2in}[n] \cong V_{2view}[n-1] - V_{22}[n-1] - V_{21}[n-1] \qquad (3)$$

For discrete-time systems, convolution operator is replaced by convolution summation as follows:

$$V_{11}[n] = S_{11}[n] * V_{1in}[n]$$
$$= \sum_{k=2}^{n} S_{11}[n-k+1]V_{1in}[k] + S_{11}[n]V_{1in}[1] \qquad (4)$$

$$V_{12}[n] = S_{12}[n] * V_{2in}[n]$$
$$= \sum_{k=2}^{n} S_{12}[n-k+1]V_{21in}[k] + S_{12}[n]V_{2in}[1] \qquad (5)$$

In the opposite port, similar results can be obtained.

The voltage sources are imposed at the input ports. For example, $V_{11}(t) + V_{12}(t)$ and $V_{21}(t) + V_{22}(t)$ are excitation at ports 1 and 2, respectively. Besides, the input ports are terminated by 50Ω load resistor.

Because the proposed approach is suitable for the arbitrary incident wave, the incident waves do not have to be calculated in advance on microstrip lines.
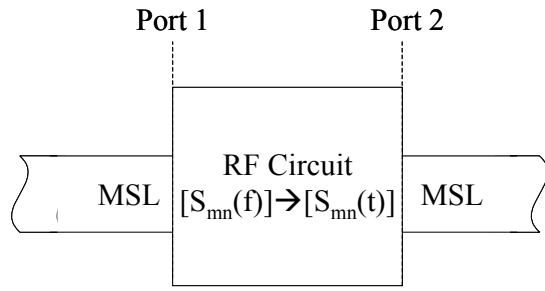
III   IMPLEMENTATION AND APPLICATION

An example—an amplifier circuit at 0.65GHz—is considered to check the efficiency and accuracy of this method. In our simulation, the amplifier model consists of a transistor, matching circuits, and bias circuit. The circuit of the amplifier is shown in Fig. 2. The substrate characterized by a relative permittivity is 2.6 and thickness is 0.8mm. C, R, and S are capacitance, resistance, and stub, respectively. MSL1 and MSL3 are 50Ω microstrip lines. MSL2 is 100Ω microstrip line. L and W are length and width of microstrip line. Base and collector voltages are 0.8V and 5.0V, respectively. The reference planes are RF In and RF Out as shown in Fig.2. The input impedance and $|S_{21}|$ are measured. In the measurement condition, the conduction of the transistor is linear at $V_{CE} = 5[V]$, $I_c = 10[mA]$, and input RF power –35[dBm]. Fig. 3 and 4 show the calculated and measured input impedances and $|S_{11}|$, respectively. Fig. 5 shows the results of the calculated and measured $|S_{21}|$. Although this model was not optimized, the measured results show similar tendency to the calculated ones. The proposed method verifies the capability of the extended FDTD method in dealing with nonlinear active RF circuits.
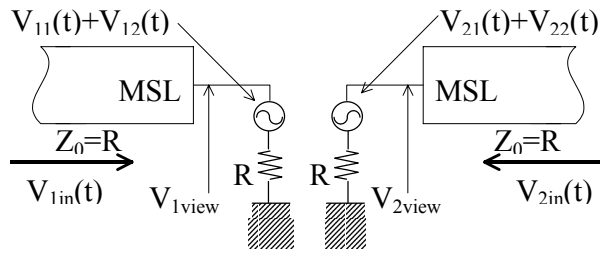
III. CONCLUSIONS

New FDTD method using the S-parameters of an RF circuit has been proposed. Then, this method is evaluated by employing it for an RF amplifier circuit. The results obtained by this method are in good agreement with the measurements. So, the proposed method is useful to analyze various RF circuits.

REFERENCES

[1]   V. A. Thomas, M. E. Jones, M. J. Picket-May, A. Taflove, and E. Harrigan, "The use of SPICE lumped circuits as subgrid models for FDTD high-speed electronic circuit design," *IEEE Microwave and Guided Wave Letters*, vol.4, No.5, 1994, pp. 141-143.

[2]   B. Toland, B. Houshumand, and T.Itoh, "Modeling of nonlinear active regions with the FDTD method, " *IEEE Microwave Guided Wave Letter*, vol. 3, pp. 333-335, Sept. 1993.

[3]   X. Ye and J. L. Drewniak, "Incorporating two-port networks with S-parameters into FDTD," *IEEE Microwave and Wireless Components Letters*, Vol. 11, No. 2, 2001-2.

Port 1   Port 2

MSL | RF Circuit $[S_{mn}(f)] \rightarrow [S_{mn}(t)]$ | MSL

(a)

$V_{11}(t)+V_{12}(t)$ $V_{21}(t)+V_{22}(t)$

MSL   MSL

$Z_0=R$ R   R $Z_0=R$

$V_{1in}(t)$ V_{1view} V_{2view} $V_{2in}(t)$

(b)

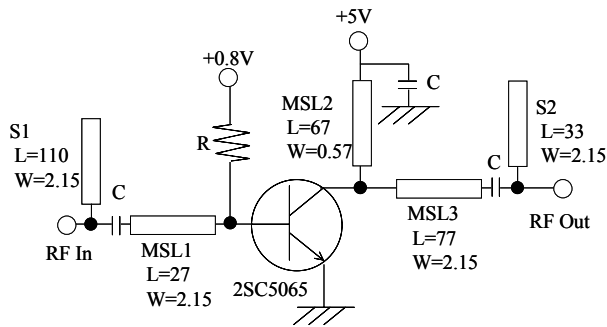Fig. 1   (a)Two-port RF circuit and a microstrip line.

(b) time-domain equivalent circuit.

Fig. 2   Circuit of the amplifier. Equivalent circuit with lumped capacitors and resistors, transmission lines, voltage source, and the transistor.
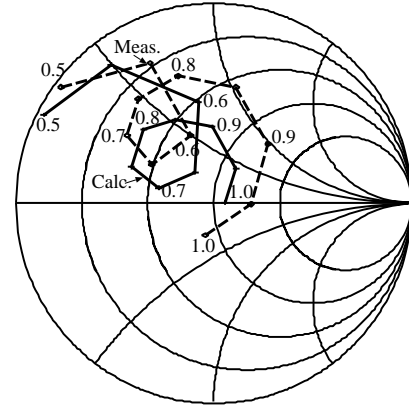

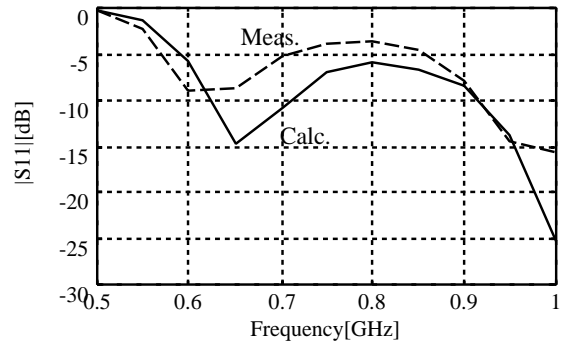Fig. 3   Comparison between calculated (solid) and measured (dashed) input impedance at port 1.

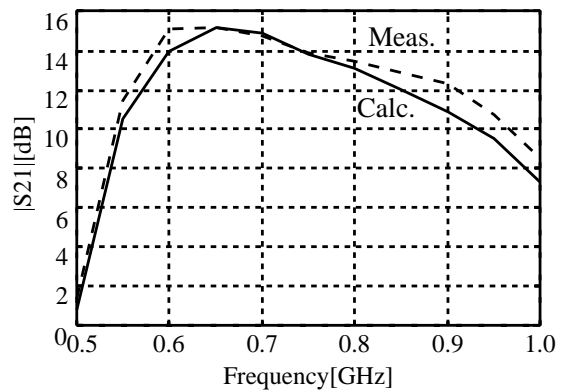Fig. 4   Comparison between calculated (solid) and measured (dashed) magnitude of S_{11}.

Fig. 5   Comparison between calculated (solid) and measured (dashed) magnitude of S_{21}.

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