FDTD 방법을 이용한 단일 계단형 마이크로스트립 기판 불연속의 등가회로 개발

Finite-Difference Time-Domain Approach for the Development of an Equivalent Circuit for a Single Step Microstrip Discontinuity in the Substrate

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요 약

본 논문에서는 유한차분 시간영역 방법을 적용하여 단일 계단형 마이크로스트립 기판 불연속 구조를 해석하였으며, 이 결과를 사용하여 LC 등가회로를 구성하였다. 본 논문에서 제안된 구조는 마이크로스트립 선로의 길이 방향으로 계단형 기판 불연속을 가지며, 패치 안테나의 급전선, 회로 모듈간 연결 등에 적용될 수 있다. FDTD 해석결과는 HFSS를 이용하여 얻어진 결과와 비교하여 잘 일치함을 보였다. 개발된 등가회로는 S_{11}과 S_{21} 모두 2.4% 이내의 정확도를 가지며, 마이크로파 회로의 CAD 설계에 응용될 수 있다.

Abstract

The finite-difference time-domain (FDTD) method is applied to analyze a single step microstrip discontinuity in the substrate, and an equivalent circuit model comprised of two inductors and a capacitor has been developed using the numerical results. The microstrip discontinuity newly introduced in this paper has a thickness change of the substrate in the longitudinal direction with a uniform strip width. The discontinuity can be applied to the feeding circuit design for the patch antennas and interconnections between microwave circuit modules. The simulation results are compared with those computed by HFSS, and two results showed a good agreement. An equivalent circuit developed from the FDTD results, which is accurate within 2.4% in magnitudes of S_{11} and S_{21}, can be applied for the computer-aided design of microwave circuits.

Ⅰ. INTRODUCTION

An accurate characterization for the discontinuities of the microstrip line is very important for the design of microwave circuits. So extensive research results for the discontinuity analysis have been published[1]~[3]. Among the various forms of microstrip discontinuities, transitions between different types of structures, such as triplate-to- microstrip[4], coaxial-to-microstrip[4], and microstrip-to-microstrip[5], have been analyzed for the usage in the antenna feeding systems. And similar structures have been dealt for an interconnection between microwave integrated circuit (MIC) and monolithic microwave integrated

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circuit (MMIC) modules[6] and a double step microstrip discontinuity in the substrate[7].

In this research, we characterize a single step microstrip discontinuity in the substrate to illuminate the effect of a substrate thickness change in the microstrip line with a uniform strip width, and the equivalent circuit for the given structure is presented. To analyze the proposed discontinuity, we use the FDTD method. The FDTD method, first formulated by Yee[8], has several advantages in the viewpoint of the flexibility in modeling complex circuit structures and its simplicity in the computer program implementation of Maxwell's equations. But no perfect boundary condition to confine the computational domain has been developed yet. And this method requires large computer memory and high speed CPU, so mesh parameters must be chosen appropriately. The background theory for the FDTD method is explained briefly in section Ⅱ before the numerical simulation is performed in section Ⅲ. In section Ⅲ, an equivalent circuit for the single step microstrip discontinuity in the substrate is developed from the results of the FDTD simulation.

Ⅱ. FINITE-DIFFERENCE TIME-DOMAIN METHOD

Maxwell's curl equations in the homogeneous and lossless medium can be expressed as Eq. (1) and (2)[9].

$$\mu\frac{\partial\vec{H}}{\partial t}=-\nabla\times\vec{E} \tag{1}$$

$$\varepsilon\frac{\partial\vec{E}}{\partial t}=\nabla\times\vec{H} \tag{2}$$

where $\vec{E}$ is the electric field, $\vec{H}$ is the magnetic field, ε is the permittivity, and μ is the permeability. The FDTD method is developed to compute $\vec{E}$ and $\vec{H}$ at each node in the computational domain, using the difference equations discretized from the curl eqμations. For example, the difference equations for $H_x^{n+1/2}(i,j,k)$ and $E_x^{n+1}(i,j,k)$ around a node (i,j,k) at time step n are given as follows:[10]

$$\begin{aligned} H_x^{n+1/2}(i,j,k)&=H_x^{n-1/2}(i,j,k)\\ &-\frac{\Delta t}{\mu}\left[\frac{E_z^n(i,j,k)-E_z^n(i,j-1,k)}{\Delta y}\right]\\ &+\frac{\Delta t}{\mu}\left[\frac{E_y^n(i,j,k)-E_y^n(i,j,k-1)}{\Delta y}\right] \end{aligned} \tag{3}$$

$$\begin{aligned} E_x^{n+1}(i,j,k)&=E_x^n(i,j,k)\\ &+\frac{\Delta t}{\varepsilon}\left[\frac{H_z^{n+1/2}(i,j+1,k)-H_z^{n+1/2}(i,j,k)}{\Delta y}\right]\\ &-\frac{\Delta t}{\varepsilon}\left[\frac{H_y^{n+1/2}(i,j+1,k)-H_y^{n+1/2}(i,j,k)}{\Delta z}\right] \end{aligned} \tag{4}$$

where Δx, Δy, and Δz are the mesh size for each coordinate, and Δt is the time step. Other components can be obtained similarly applying the central difference approximation for differentiation. If a node is located at the boundary of several media, the average permittivity, $\sum_{i=1}^{m}\varepsilon_i/m$, is used. For the numerical stability of the difference equations, the stability condition, so called Courant condition, must be satisfied,[10]

$$c\Delta t\le[(\Delta x)^{-2}+(\Delta y)^{-2}+(\Delta z)^{-2}]^{-1/2} \tag{5}$$

where $c=1/\sqrt{\mu\varepsilon}$ is the speed of light in the material being modeled. Δx, Δy, and Δz must be chosen properly for field values to have enough space resolution, and Δt for enough frequency resolution.

The leap-frog algorithm where the magnetic and electric fields are calculated alternately from each other for time-marching begins as an excitation pulse is applied on the source plane. In this paper, we adopted a static electric field distribution across the source plane to obtain numerically stable results. The excitation pulse can be expressed with the time variation of Gaussian function as follows:[7]

$$E_x(t)=e_{x0}e^{-(t-t_0)^2/T^2} \tag{6}$$

$$E_y(t)=e_{y0}e^{-(t-t_0)^2/T^2} \tag{7}$$

where e_{x0} and e_{y0} represent x and y components of the static electric field in the source plane, respectively. The static field can be obtained easily by applying the finite difference method (FDM) to the source plane. The electrostatic field distributions across the source plane of the microstrip line to be analyzed in this paper are shown in Fig. 1 for an illustrative purpose. Parameter t_0 is used to avoid abrupt perturbation in the excitation and T to control the pulse width which affects the frequency range in the analysis.

Various absorbing boundary conditions (ABC) are proposed to confine the modeling space and to absorb the reflected wave from the discontinuity at the source plane. Here the time-space extrapolation technique is applied[11].

$$E_i(N_z \triangle z, n\triangle t) = E_i[(N_z-1)\triangle z, (n-n_t)\triangle t] \quad (8)$$

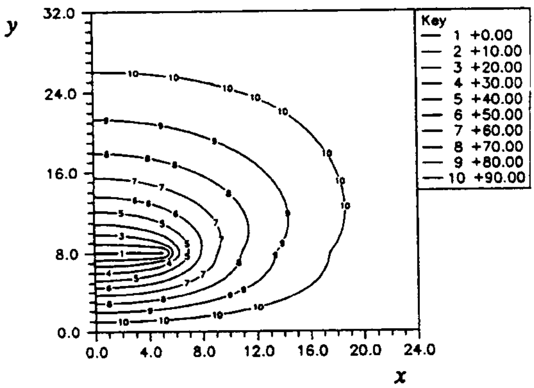
where N_z is the node index at the boundary plane in the z direction, n_t is the number of time steps required for the incident wave to travel one mesh size $\triangle z$.

Characteristic impedance Z_0 of the microstrip line is calculated from the ratio of the voltage $V(f)$ to the current $I(f)$ as Eq. (9)[7].

$$Z_0 = \frac{V(f)}{I(f)} e^{j(-\omega\triangle t/2+\beta\triangle z/2)} \quad (9)$$

where $V(f)$ is the Fourier transform of the line integration of the electric field from the center of the metal strip to the ground plane, and $I(f)$ is the Fourier transform of the closed-contour integration of the magnetic field around the metal strip. The phase correction factor in Eq. (9) is to compensate that electric and magnetic fields are calculated half the time step away and half the mesh length apart.

Fig. 2 shows the perspective view of a microstrip single step discontinuity in the substrate. To simplify



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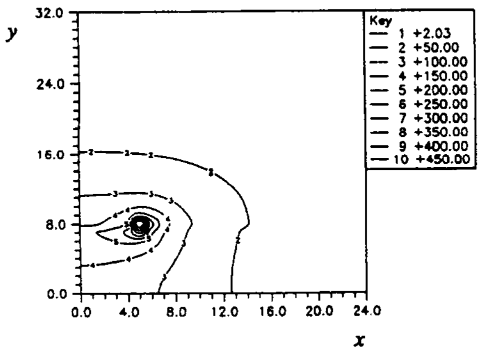

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Fig. 1. Static electric field distributions across the source plane of the microstrip line.
(a) Potential distribution.
(b) Contour plot of $|\vec{E}_y|$.

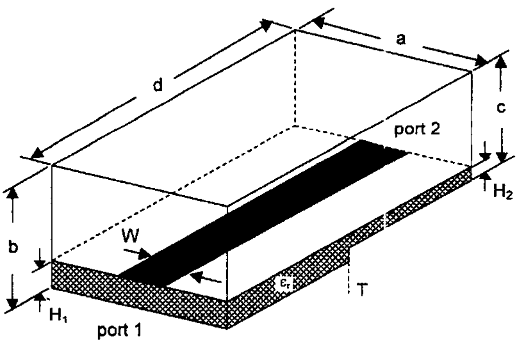


Fig. 2. P.erspective view of a microstrip single step discontinuity in the substrate.
$a=50\Delta x$, $b=32\Delta y$, $c=27\Delta y$, $d=400\ \Delta z$, $W=10\Delta x$, $H_1=8\Delta y$, and $H_2=3\Delta y$, $\varepsilon_r=10.2$.

computations, the microstrip structure is shielded with four electric walls. The width of the enclosing box is five times larger than the strip width, and the height is four and nine times larger than the substrate height in the port 1 side and in the port 2 side, respectively. For the shielded uniform microstrip line of 50Ω on the substrate with the dielectric constant of 10.2 and the thickness of 0.635 mm, the lowest cutoff frequency of the higher order modes is calculated as 36 GHz[12]. Thus the chosen box size is adequate for the analysis in the frequency range from dc to 30 GHz.

As a preparatory procedure for the S-parameter calculation, the analysis of the corresponding uniform microstrip line is required. Fig. 3 shows the calculated results from the FDTD method for characteristic impedances of uniform microstrip lines having the same strip width and dielectric constant but different substrate thickness. In this figure, Z_{01} represents the characteristic impedance for the structure of the port 1 side and Z_{02} for the structure of the port 2 side. For a two-port circuit having different characteristic impedance at each port, the generalized S-parameters can be expressed as[9].

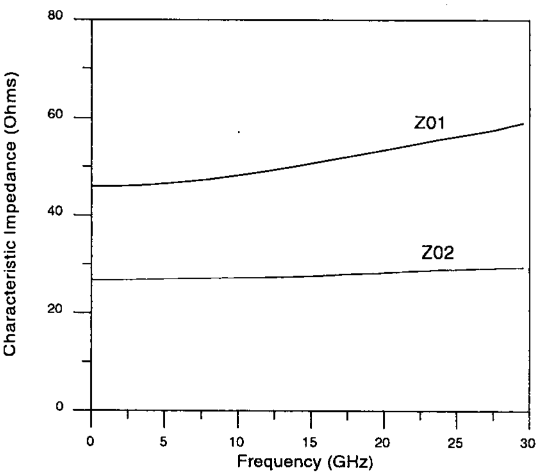


Fig. 3. Characteristic impedances of uniform shielded lines. $W=0.593$ mm, ($\varepsilon_r=10.2$, H_1=0.635 mm for Z_{01}, and H_2=0.238 mm for Z_{02}.

$$S_{ij}=\left[\frac{V_i^- \sqrt{Z_{0j}}}{V_j^+ \sqrt{Z_{0i}}}\right]_{V_k^+=0 \text{ for } k\neq i} \qquad i,\ j=1 \text{ or } 2 \tag{10}$$

where superscripts + and represent the incident and reflected waves, respectively. The generalized S-parameters are used in this paper.

Ⅲ. NUMERICAL SIMULATION AND EQUIVALENT CIRCUIT

The dimensions of a microstrip single step discontinuity in the substrate shown in Fig. 2 are $W=10\Delta x$, $H_1=8\Delta y$, and $H_2=3\Delta y$, with $\varepsilon_r=10.2$. The size of the computational domain is $50\Delta x\times 32\Delta y\times 400\Delta z$, and the number of time iterations are 4000. The mesh parameters are $\Delta x=0.0593$ mm, $\Delta y=0.0794$ mm, $\Delta z=0.0875$ mm, and $\Delta t=1.26785$ μs. The longitudinal space increment Δz is less than $\lambda_g/20$, so the numerical dispersion can be neglected[10]. The parameters of the Gaussian time function are $t_0=600\Delta t$ and T=60 Δt. Here space and time increments are chosen so that the Courant condition is satisfied, and the number of time steps required for the pulse to travel one longitudinal space step is six for the time-space extrapolation absorbing boundary condition. Fig. 4 shows the time-domain field distribution just beneath

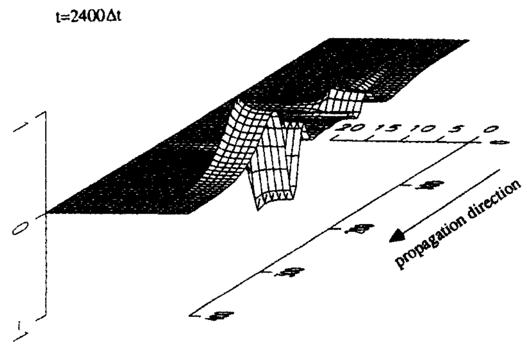
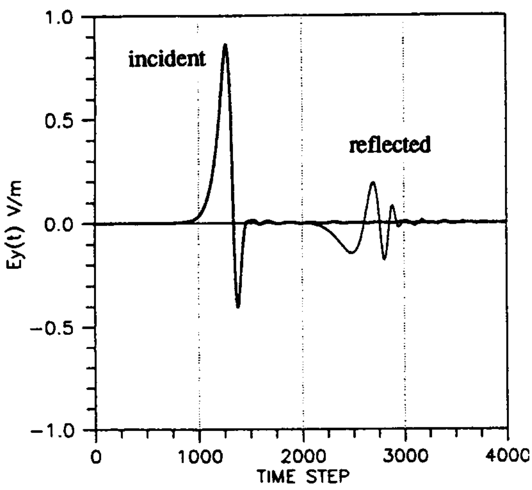


Fig. 4. Time domain field distribution of Gaussian pulse propagation and reflection at 2400 time steps.



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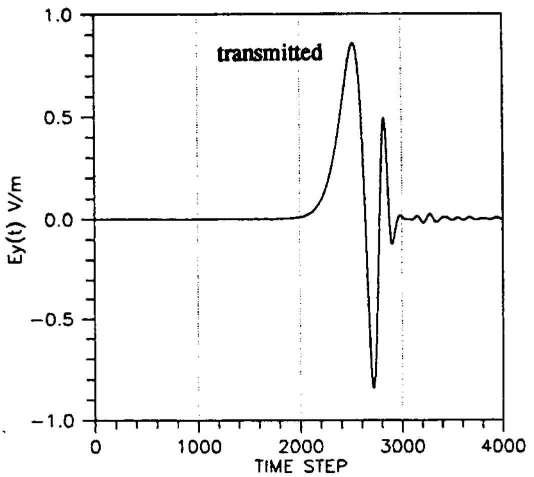
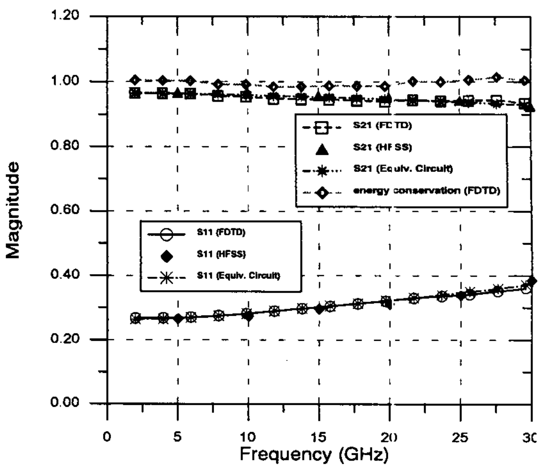


(b)

Fig. 5. Time domain signals observed at 50 Δz away from the reference plane for the single step discontinuity. (a) Incident and reflected signals. (b) Reflected signal.



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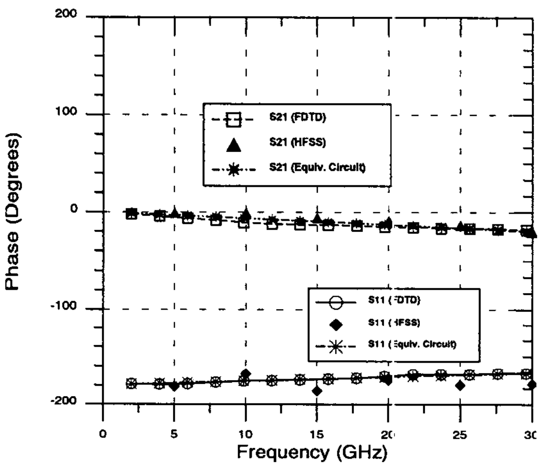

(b)

Fig. 6. S_{11} and S_{21} for the single step discontinuity. (a) Magnitudes. (b) Phases.

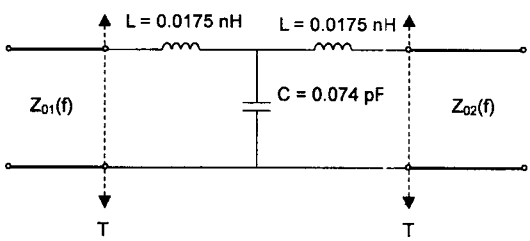

Fig. 7. Equivalent circuit for the single step discontinuity shown in Fig. 2.

the microstrip at 2400 time steps. The incident, reflected, and transmitted waves for the whole time duration, observed at 50 Δz away from the reference plane T, are shown in Fig. 5. In this figure, we can notice that the field amplitude of the transmitted wave is larger than that of the incident wave because the substrate thickness of the port 2 side is decreased compared with that of the port 1 side. The S-parameters obtained from the time domain simulation are presented in Fig. 6, and they are compared with those computed by HFSS[13]. There is a good agreement between the two results and the energy conservation property in the closed structure is well satisfied. It is observed that the magnitudes of the S-parameters exhibit quite a flat variation as the frequency increases as in the microstrip step-in-width[3]. And it can be noticed that the single step discontinuity has a considerable discontinuity effect. The computation time for this FDTD simulation is about 12 hours on a HP730 workstation.

The single step discontinuity is modeled with an equivalent circuit from the S-parameters computed by the FDTD method. The equivalent circuit shown in Fig. 7 is comprised of two series inductors and one parallel capacitor. The S-parameters computed from the equivalent circuit are shown in Fig. 6 to check its validity. The equivalent circuit well represents the single step discontinuity for the frequency range up to 30 GHz within 2.4% in magnitudes of S_{11} and S_{21}.

Ⅳ. CONCLUSION

A single step microstrip discontinuity in the substrate has been analyzed using the finite-difference time-domain method. The numerical results show that the magnitudes of the S-parameters exhibit quite a flat variation in the wide range of frequency. Using the S-parameters obtained from the FDTD method, an equivalent circuit is developed for the single step discontinuity, which is useful for a simulation in the computer-aided design. The analysis results for the discontinuity are applicable to the design of patch antenna feeding circuits or interconnections between microwave circuit modules.

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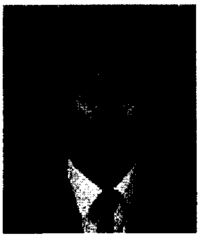

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