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Analysis of a Double Step Microstrip Discontinuity in the Substrate Using the 3-D-FDTD Method

Joong Chang Chun and Wee Sang Park

***Abstract*—The finite-difference time-domain (FDTD) method has been applied to the analysis of a double step microstrip discontinuity having thickness changes in the longitudinal direction. The discontinuity occurs in patch antenna feeds or interconnections between microwave planar circuit modules. The simulation results are compared with those computed by HFSS to show a good agreement. An equivalent circuit for the double step discontinuity is developed from the scattering parameters computed by the FDTD method.**

I. Introduction

The planar microwave circuits, microwave integrated circuit (MIC) and monolithic microwave integrated circuit (MMIC), are playing an important role in the development of mobile and satellite communication systems. Among the various forms of planar transmission lines the microstrip line is used most commonly because of its simple structure and extensive research results obtained experimentally or theoretically [1]. Therefore, an accurate analysis of the discontinuities such as step-in-width, open end, gap, bend, T-junction, cross-junction, slit, and slot is essential to the circuit design of filters, matching circuits, transitions, and interconnections [2]. Recently, some microwave applications of transitions or interconnections between two substrates with different permittivities or different thicknesses were reported in [3] and [4], while in the area of optical integrated circuits the discontinuities of permittivity or height have been analyzed by many researchers [5]–[7]. From this point of view, we are interested in the microstrip discontinuities which have changes in the substrate height along the direction of wave propagation.

In this paper, a microstrip discontinuity due to the change of substrate height is analyzed by means of the three-dimensional (3-D) finite-difference time-domain (FDTD) method. The FDTD method, first proposed by Yee [8], is widely used nowadays in the analysis of microstrip discontinuities with the development of computer hardware technology. This method has several advantages in the flexibility of modeling discontinuities and its simplicity in the computer program implementation of Maxwell equations [9]. But no perfect boundary condition for the FDTD method has been developed as yet. Also this method requires large computer resources, which demand proper choice of mesh parameters for computation. The discontinuities for a two-port microstrip line bear various forms such as the changes in the substrate height and permittivity as well as in the strip width. The discontinuity treated in this work is a double step in the substrate height with a uniform strip width and a constant permittivity.

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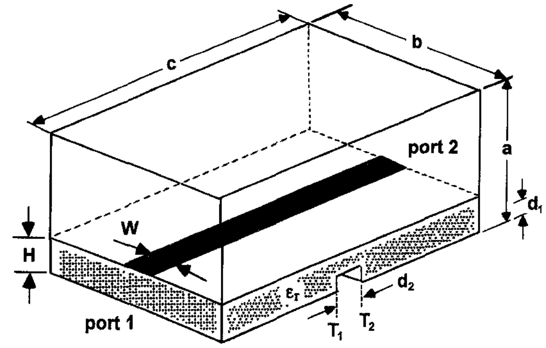

Fig. 1. Perspective view of a microstrip double step discontinuity in the substrate. $a = 5H$, $b = 4W$, $W = 0.593$ mm, $\epsilon_r = 10.2$, $H = 0.635$mm, $d_1 = 0.397$mm, and $d_2 = 0.700$mm.

II. Analysis Method

The FDTD method is well formulated for the analysis of microstrip circuits in several papers [10]–[12]. But the method can be improved by using an excitation pulse whose field configuration is similar to that of the dominant mode of the microstrip line. The excitation pulse used in this research is composed of a quasi-static electric field in the cross section and the time variation of Gaussian function as follows:

$$E_x(t) = e_{x0}e^{-(t-t_0)^2/T^2} \tag{1}$$

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

where e_{x0} and e_{y0} represent x- and y- components of the quasi-static electric field in the source plane, respectively. The quasi-static field can be easily calculated by the finite difference method [13], and it contains much less components of the higher order modes than the uniformly distributed field under the metal strip [10], [11]. Thus using the quasi-static field yields more stable numerical result.

The propagation constant β and the effective dielectric constant ϵ_{reff} can be calculated from the ratio of the electric fields taken at two nodes a certain distance apart from each other as explained in [10]. But the characteristic impedance Z_0 should be calculated carefully because the electric and magnetic nodes are placed off in space by one half of the space step, and the evaluation of field components is made also at alternate half-time steps. Thus a phase correction factor in the form of an exponent as in (3) has to be included in the usual formula [10]

$$Z_0 = \frac{V(f)}{I(f)}e^{-j\omega\Delta t/2+j\beta\Delta z/2} \tag{3}$$

where $V(f)$ is the line integral of the electric field under the center of the strip, and $I(f)$ is the loop integral of the magnetic field around the metal strip. For the absorbing boundary condition, the time-space extrapolation method [14] applied to the super-absorbing boundary condition [15] is used.

As a preparatory procedure for the S-parameter calculation of a microstrip discontinuity, an analysis of the corresponding uniform

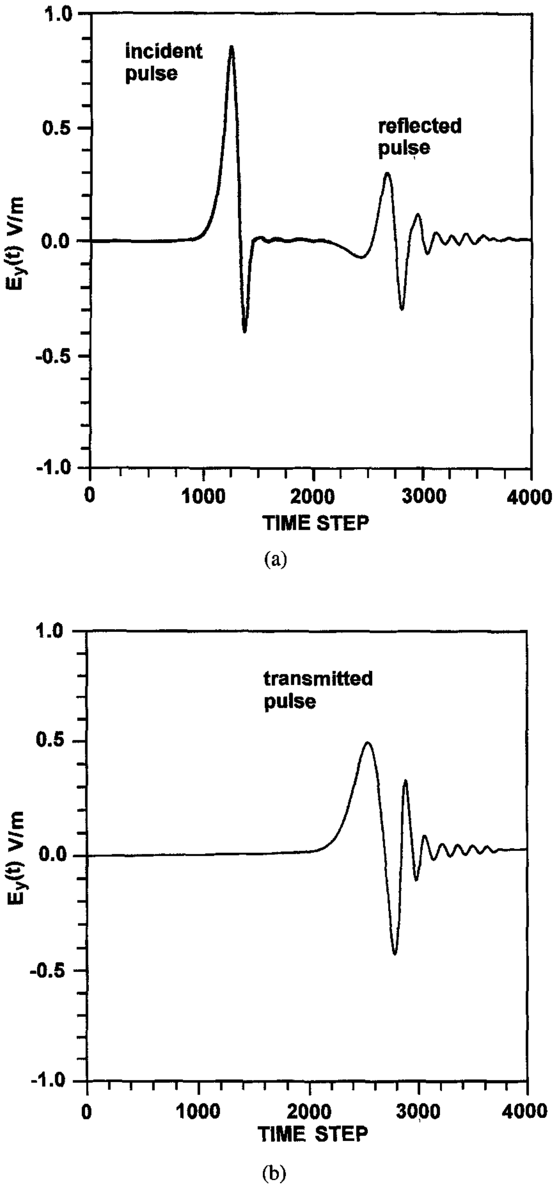

Fig. 2. Time domain signals observed at $50\Delta z$ away from the reference planes T_1 and T_2 for the double step discontinuity. (a) Incident and reflected pulses. (b) Transmitted pulse.

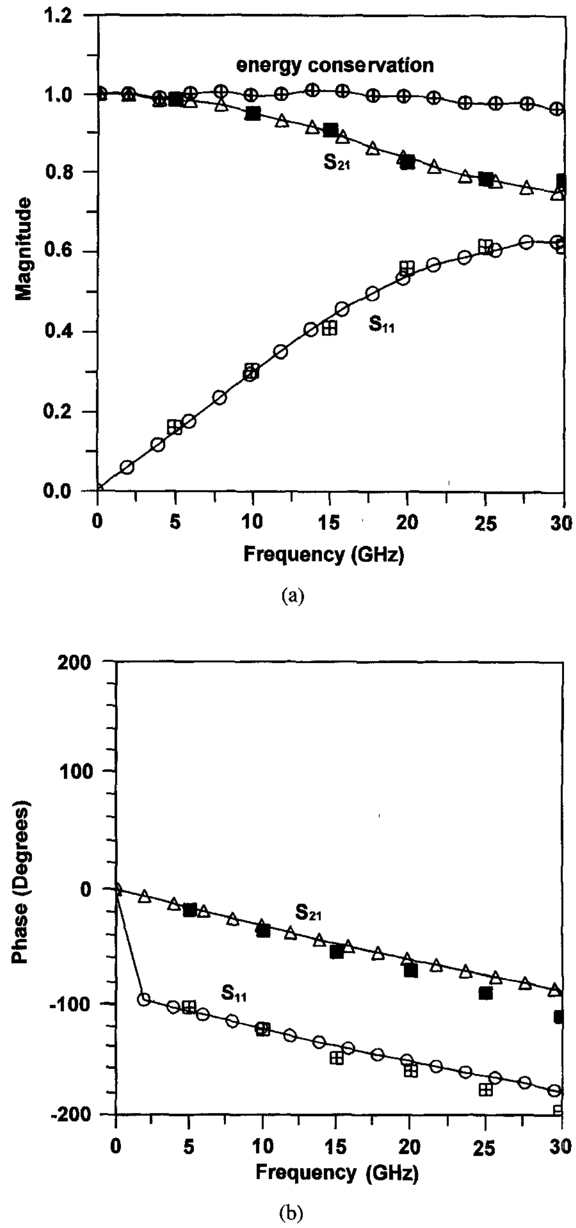

Fig. 3. S-parameters for the double step discontinuity. (a) Magnitudes and (b) phases of S_{11} and S_{21}. –○– : S_{11}; –△– : S_{21}; –⊕– : energy conservation by FDTD. –⊞– : S_{11}; –■– : S_{21} by HFSS.

microstrip line is required. If the uniform microstrip line is enclosed by a shielding structure, the effect of shielding on the calculation of the characteristic impedance and the effective dielectric constant must be taken into account because the shielded microstrip line produces rather smaller values of characteristic impedance and effective dielectric constant than the corresponding open structure. According to Wu *et al.* [16] and Bahl [17], however, the effect is negligible for the shielding box whose width is greater than ten times of the strip width and whose height is greater than seven times of the substrate height. This is true for the effective dielectric constant, but the characteristic impedance for such an enclosed structure is still smaller than that for the open structure. Moreover the higher order modes caused by the enclosure should be considered in the analysis with the FDTD method. The larger the box size, the smaller becomes the frequency range of analysis because the lowest cutoff frequency for the higher order modes decreases. Therefore, the box size must be chosen such that the higher order modes should not propagate in the frequency range of analysis. Moore *et al.* [18] have selected the width and height of the shielding box three times as large as the metal strip and the substrate height, respectively. In this research, the width of the enclosing box is four times larger than the strip width, and the height is five times larger than the substrate thickness. For the uniform microstrip line of 50 Ω on the duroid substrate with the dielectric constant of 10.2 and the substrate thickness of 0.635 mm, the lowest cutoff frequency of the higher order modes is calculated as 36 GHz from the two-dimensional (2-D)-FDTD method [19]. So the chosen box size is adequate for the analysis in the frequency range of dc to 30 GHz.

III. Numerical Results

A microstrip double step discontinuity in the substrate is shown in Fig. 1. The dimensions are $W = 0.593$ mm, $H = 0.635$ mm, $d_1 = 0.397$ mm, and $d_2 = 0.700$ mm, with $\epsilon_r = 10.2$. The size of the computation domain is $48\Delta x \times 32\Delta y \times 400\Delta z$, and the number

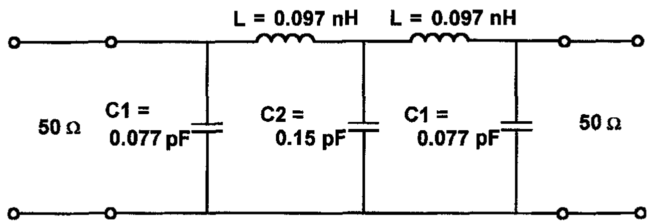

Fig. 4. Equivalent circuit for the double step discontinuity.

of time iterations is 4000. The mesh parameters are $\Delta x = W/10 = 0.0593$ mm, $\Delta y = H_1/8 = 0.0794$ mm, $\Delta z = 0.0875$ mm, and $\Delta t = 0.126\,785 \mu$sec. The parameters of the Gaussian time function are $t_0 = 600\Delta t$ and $T = 60\Delta t$. Here Δt is chosen so that the Curant condition is satisfied, and the number of time steps required for the pulse to travel one longitudinal space step is six in the time-space extrapolation absorbing boundary condition [14]. The incident, reflected, and transmitted waves, observed at $50\Delta z$ away from the reference planes T_1 and T_2, are shown in Fig. 2. The S-parameters are obtained from the Fourier transform of the time domain simulation, and they are compared with those computed by HFSS [20] as shown in Fig. 3. There is a good agreement between the two results. Also the energy conservation property is well satisfied. It is observed that the magnitude of the reflection coefficient increases almost linearly with the increase of frequency.

To illustrate the usefulness of the FDTD analysis an equivalent circuit corresponding to the double step discontinuity is developed. The equivalent circuit shown in Fig. 4 consists of five lumped elements, three parallel capacitors and two series inductors, and the circuit seems to bear the characteristics of a low-pass filter. It is claimed that the equivalent circuit well represents the double step discontinuity for the frequency range from 3.9 GHz to 29.6 GHz within 2.6% in the magnitudes of S_{11} and S_{21}.

IV. Conclusion

The simulation results by the finite-difference time-domain method for a double step microstrip discontinuity in the substrate have been presented. The magnitude of the reflection coefficient for the double step discontinuity increases almost linearly as the frequency increases. Using the FDTD results for the double step discontinuity, an equivalent circuit is developed, 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 feeds or interconnections between microwave circuit modules.

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