논문 2012-50-3-3

다층 기판위의 대칭 및 비대칭의 다중 결합선로에 대한 해석

(Analysis of Symmetric and Asymmetric Multiple Coupled Line on the Multi-layer Substrate)

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(Yoonsuk Kim and Minsu Kim)

요 약

n 개의 균일한 결합선로를 해석하기 위하여 2n-port 어드미턴스 매트릭스의 추출에 기초한 일반적인 특성화 절차가 제시된다. 본 논문에서는 비대칭 다중 결합선로를 해석하기 위하여 시간영역의 유한차분법을 사용하여 정규화 모드 파라미터 접근법의 적용을 제안한다. 주파수 의존적인 정규화 모드 파라미터는 2n-port 어드미턴스 매트릭스로부터 얻어지고, 이로부터 주파수 의존적인 전파상수와 유효 유전율 및 결합선로의 특성임피던스를 계산할 수 있다. 이 기법을 설명하기 위해 몇몇의 실질적인 다중 유전체 상의 결합선로 구조들이 모의 실험되었으며, 특히 전도체가 유전체 사이에 내재된 형태의 선로가 해석되었다. 시간영역 유한 차분법을 활용한 결과는 Spectral Domain Method의 모의실험 결과와 비교하였고, 잘 일치함을 보였다. 시간영역의 특성화 절차에 기인한 유한차분법은 얇거나 두꺼운 혼성 구조 뿐 아니라 다층 PCB상의 다중의 전도체 결합 선로 설계를 위한 훌륭한 광대역 모의실험 도구가 됨을 볼 수 있다.

Abstract

A general characterization procedure based on the extraction of a 2n-port admittance matrix corresponding to n uniform coupled lines on the multi-layered substrate using the Finite-Difference Time-Domain (FDTD) technique is presented. In this paper, the frequency-dependent normal mode parameters are obtained from the 2n-port admittance matrix to analyze multi-layered asymmetric coupled line structure, which in turn provides the frequency-dependent propagation constant, effective dielectric constant, and line-mode characteristic impedances. To illustrate the technique, several practical coupled line structures on multi-layered substrate have been simulated. Especially, embedded conductor structures have been simulated. Comparisons with Spectral Domain Method are given, and their results agree well. It is shown that the FDTD based time domain characterization procedure is an excellent broadband simulation tool for the design of multiconductor coupled lines on multilayered PCBs as well as thick or thin hybrid structures.

Keywords : FDTD technique, Propagation constant, Effective dielectric constant, Characteristic impedance,

Ⅰ. INTRODUCTION

Accurate characterization of multiconductor coupled lines using electromagnetic modeling and simulation tools plays an important role in the design of high speed transmission line structures in multilayer media. Uniformly multiple coupled line systems are widely used in filters, directional couplers and impedance matching networks at microwave frequencies[1~3]. Time domain techniques can be used directly for time domain simulation, as a virtual TDR(Time-Domain Reflectometry) to derive distributed models, and to find broadband frequency-dependent properties of multi-conductor structures[4~8]. Even though the extraction procedure for multiple coupled line parameters from time domain computations is well understood in principle,

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※ 본 논문은 '2012년도 공군사관학교 국고연구비 지원으로 수행된 것임.
접수일자: 2012년11월13일, 수정완료일: 2013년2월18일

explicit CAD oriented techniques have not been reported. Characterization procedures for multiconductor lines in a homogeneous medium and symmetrical multiple coupled lines in an inhomogeneous media have been formulated in terms of input voltage and currents of the coupled line systems and the resulting input reflection coefficient or admittance matrix[5]. The normal mode parameters and the equivalent line constants for the multiconductor lines are derived in this paper from the 2n port admittance matrix.

Tripathi et al. reported analytical and numerical techniques for the pulse propagation characteristics in multilevel interconnections associated with high-speed digital ICs including VLSI chips[9]. Chan et al. presented the propagation characteristics of waves along a periodic array of parallel signal lines in a multi-layered structure in the presence of a periodically perforated ground plane and the characterization of the discontinuities made of two orthogonally crossed strip lines on a suspended substrate[10].

In [11-13], Kim presented the analysis for symmetric structures on various lossy media using the Finite-Different Time-Domain(FDTD) technique. He proposed the new crossbar embedded structure and gave the frequency-dependent parameters. But those works are limited to symmetric structures.

In this research, a general characterization procedure based on the extraction of a 2n-port admittance matrix corresponding to n uniform coupled lines on the multi-layered substrate using the FDTD technique is presented. And then, simulation results are given for two layered three coupled line embedded structures as an example.

Ⅱ. MODELING OF MULTI-LAYERED SYMMETRIC AND ASYMMETRIC MULTI COUPLED LINE

The dispersion characteristics of a transmission line can be described by the effective dielectric constant $\epsilon_{eff}(\omega)$ as a function of frequency. $\epsilon_{eff}(\omega)$ can be computed from the transient time solutions of voltage or current along the line in the way explained as follows. Assume V(z,t) and V(z+L,t) are monitored voltages taken at z and z+L, respectively. The Fourier transforms of V(z,t) and V(z+L,t) are denoted as $V(z,\omega)$ and $V(z+L,\omega)$ respectively. For a wave propagating in the positive z-direction, $V(z,\omega)$ and $V(z+L,\omega)$ are related by

$$V(z+L,\omega)=V(z,\omega)\exp(-\gamma(\omega)L) \tag{1}$$

where

$$\gamma(\omega)=\alpha(\omega)+j\beta(\omega) \tag{2}$$

The effective dielectric constant $\epsilon_{eff}(\omega)$ is defined through $\beta(\omega)$ as

$$\beta(\omega)=\omega\sqrt{\mu\epsilon_0\epsilon_{eff}} \tag{3}$$

i.e.,

$$\begin{aligned}\epsilon_{eff} &= \frac{\beta^2}{\omega^2\mu\epsilon_0} \\ &= \frac{1}{\omega^2\mu\epsilon_0}\left\{\frac{1}{L}im\left[\ln\left(\frac{V(z,\omega)}{V(z+L,\omega)}\right)\right]\right\}^2\end{aligned} \tag{4}$$

The effective dielectric constant $\epsilon_{eff}(\omega)$ of the microstrip lines can be obtained with the FDTD method. Another characteristic quantity of the

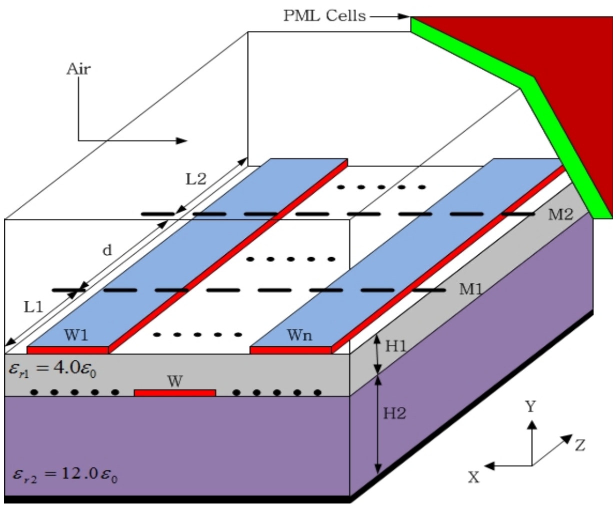


그림 1. FDTD 시뮬레이션을 위한 전체 계산영역
Fig. 1. Entire computational domain for FDTD simulation.

microstrip line is the characteristic impedance $Z_0(\omega) = V(\omega)/I(\omega)$. $V(\omega)$ is the Fourier transform of the transient voltage V(t), which is defined as the line integral of the electric field from the ground plane to the conductor strip and $I(\omega)$ is the Fourier transform of the transient current I(t).

The procedure for deriving the expression for the admittance or impedance matrix of general 2n-port is well known and is based on the solution of coupled transmission lines equations shown in (5) and (6)

$$\frac{\partial[V]}{\partial z} = -[Z(\omega)][I] \tag{5}$$

$$\frac{\partial[I]}{\partial z} = -[Y(\omega)][V] \tag{6}$$

where vectors [V] and [I] represent voltages and currents on the lines and $[Z(\omega)]$ and $[Y(\omega)]$ represent $2n \times 2n$ impedance and admittance matrices, respectively. $[Z(\omega)]$ and $[Y(\omega)]$ are related to [R], [L], [G], [C] matrices from basic equivalent circuit model of the general transmission line equations.

$$[Z(\omega)] = [R] + j\omega[L] \tag{7}$$

$$[Y(\omega)] = [G] + j\omega[C] \tag{8}$$

[R], [L], [G] and [C] are the per-unit-length line constant matrices whose elements are, in general, frequency dependent. The coupled transmission line equations (1) and (2) are decoupled with the help of voltage and corresponding current eigenvector matrices $[M_V]$ and $[M_I]$ ($[M_I] = [M_V]^{-T}$), respectively, leading to the characterization of the general n lines 2n-port by its admittance matrix. Following Chin[8]

$$[Y] = \begin{bmatrix} [Y_A] & [Y_B] \\ [Y_B] & [Y_A] \end{bmatrix} \tag{9}$$

with

$$[Y_A] = [Y_{LM}] * [M_V] \cdot [\coth(\gamma_i d)]_{diag} \cdot [M_I]^T \tag{10}$$

and

$$[Y_B] = -[Y_{LM}] * [M_V] \cdot [\operatorname{csch}(\gamma_i d)]_{diag} \cdot [M_I]^T \tag{11}$$

$$[Y_{LM}]_{n \times n} = \begin{bmatrix} Y_{LM11} & \cdot & Y_{LM1n} \\ \cdot & \cdot & \cdot \\ Y_{LMn1} & \cdot & Y_{LMnn} \end{bmatrix} \tag{12}$$

where γ_i is the ith normal mode propagation constant and represents the ith eigenvalue, and d is the length of the uniformly coupled multiconductor system. $[Y_{LM}]$ is the line mode admittance matrix whose element Y_{LMkm} represents the characteristic admittance of the k th line for mth mode. The operator '$*$' was defined in [8] for [C]=[A]*[B], as a product of corresponding terms of matrices [A] and [B].

From equations (9)-(12), a matrix [P] which includes $[Y_{LM}]$, $[M_V]$, and $[(\gamma_i d)]_{diag}$ can be defined as

$$\begin{aligned} [P] &= [Y_A]^T [Y_B]^{-T} \\ &= [M_V]^{-T} [\coth(\gamma_i d)]^T_{diag} \\ &\quad \cdot [\operatorname{csch}(\gamma_i d)]^{-T}_{diag} [M_V]^T \end{aligned} \tag{13}$$

This can be simplified to

$$[P] = [M_V]^{-T} [\cosh(\gamma_i d)]^T_{diag} \cdot [M_V]^T \tag{14}$$

Equation (14) shows that the normal mode propagation constants γ_i $(i = 1, 2 \ldots. n)$ can be directly obtained from the eigenvalues of matrix [P]. Likewise, $[M_V]$ is directly found from the eigenvectors of [P]. In the case of asymmetric multiple coupled line structure, the conventional even and odd mode technique can not be applied due to asymmetry, and, hence, the normal mode parameter approach is used as an alternative. In the case of an asymmetric coupled line, the line mode admittance matrix $[Y_{LM}]$ and the voltage and corresponding current eigenvector matrices $[M_V]$ and $[M_I]$ given by equation (12) reduce to a 2 by 2 matrix with the voltage ratio R_c and R_π for the c and π modes, respectively. The line mode admittance matrix and the two eigenvectors can be written as

$$[Y_{LM}]_{2\times 2} = \begin{bmatrix} Y_{c1} & Y_{\pi 1} \\ Y_{c2} & Y_{\pi 2} \end{bmatrix} \quad (15)$$

$$[M_V] = \begin{bmatrix} 1 & 1 \\ R_c & R_\pi \end{bmatrix} \quad (16)$$

$$[M_I] = \left([M_V]^{-1}\right)^T \quad (17)$$

Here line mode impedances such as Z_c and Z_π are readily found from equation (13) and also equation (14) give us the line mode voltage ratio for symmetric and asymmetric coupled line structure.

Furthermore, for the general three coupled line case, the line mode admittance matrix $[Y_{LM}]$ and the voltage eigenvector $[M_V]$ reduce to 3 by 3 matrices for the normal modes a, b and c, respectively[8], which can be expressed as

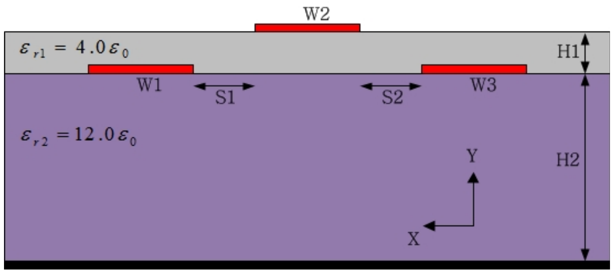
$$[Y_{LM}]_{3\times 3} = \begin{bmatrix} Y_{a1} & Y_{b1} & Y_{c1} \\ Y_{a2} & Y_{b2} & Y_{c2} \\ Y_{a3} & Y_{b3} & Y_{c3} \end{bmatrix} \quad (18)$$

$$[M_V] = \begin{bmatrix} 1 & 1 & 1 \\ R_{a2} & R_{b2} & R_{c2} \\ R_{a3} & R_{b3} & R_{c3} \end{bmatrix} \quad (19)$$

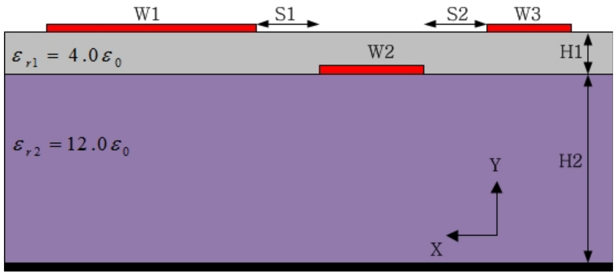
From equations (18) and (19), we can easily calculate line mode characteristic impedances and the voltage ratios of an asymmetric three coupled line for the three modes as a, b and c, respectively. For the case of a symmetric three coupled lines, $Y_{a1} = Y_{a3}$, $Y_{b1} = Y_{b3}$ and $Y_{c1} = Y_{c3}$.

Ⅲ. SIMULATION RESULTS FOR TWO LAYERED THREE COUPLED LINE EMBEDDED STRUCTURE

As the example, two layered three coupled line structures in Figure 2 are considered. As known for FDTD technique, the grid spacings should satisfy $\Delta \leq \frac{\lambda}{20}$ to ensure the accuracy of the computed spatial derivatives of the electromagnetic fields. The conductor lines are simulated on an $N_x\Delta x$ by $N_y\Delta y$ by $N_z\Delta z$ computational domain with Δx=100μm, Δy=127μm and Δz=100μm. Two layer asymmetric three coupled microstrip line of widths, W1=W2=W3=500μm(5$\triangle x$) in case 1, W1=1000μm(10$\triangle x$), W2=500μm(5$\triangle x$), W3=400μm(4$\triangle x$) in case 2, S1=S2=300μm(3$\triangle x$), with substrate thickness, H1=1270μm(10$\triangle y$), H2=635μm(5$\triangle y$), and dielectric constants, $\epsilon_{r1} = 4\epsilon_0$, $\epsilon_{r2} = 12\epsilon_0$, are considered. In all, the entire computational domain is divided into 85 by 60 by 250 grid cells including PML(Perfectly Matched Layer) cells, chosen to be large enough to not disturb the field distributions near the strips.



(a)



(b)

그림 2. 전도체 내재 이중 기판 결합 선로
(a) 대칭구조(case 1) (b) 비대칭구조(case 2)
Fig. 2. (a) symmetry structure(case 1)
(b) asymmetry structure(case 2)
two layered three coupled line embedded structure

The stability condition which needs to be satisfied is given by

$$\Delta t \leq \frac{1}{C_{\max}}\left[\frac{1}{(\Delta x)^2} + \frac{1}{(\Delta y)^2} + \frac{1}{(\Delta z)^2}\right]^{-\frac{1}{2}} \quad (20)$$

where $C_{\max}$ is the maximum phase velocity expected within the problem space. A time step of Δt=0.1855 ps is used and the total number of time steps is 1600. The input is excited with a Gaussian pulse with T=19.783 ps and t_0=59.350 ps. To apply the normal mode parameter approach, each port is excited and then voltages and currents are recorded at the positions M1 and M2 with the actual length of

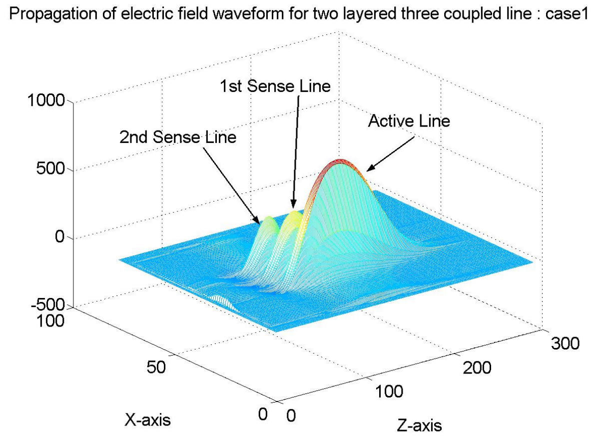


그림 3. 도체선을 따라 나타나는 전기장 파형(case 1)
Fig. 3. Electric field waveform along the conductors for case 1.

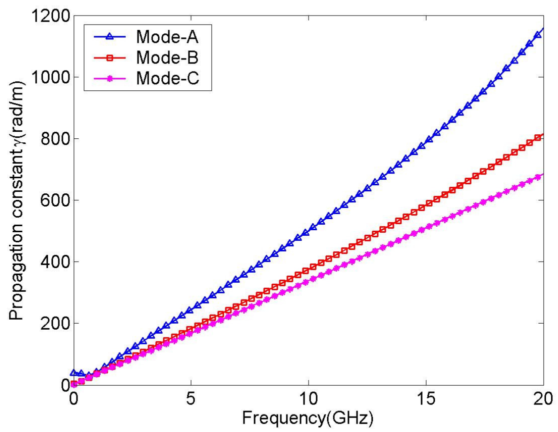


그림 4. 전파상수(case 1)
Fig. 4. Propagation constant for case 1.

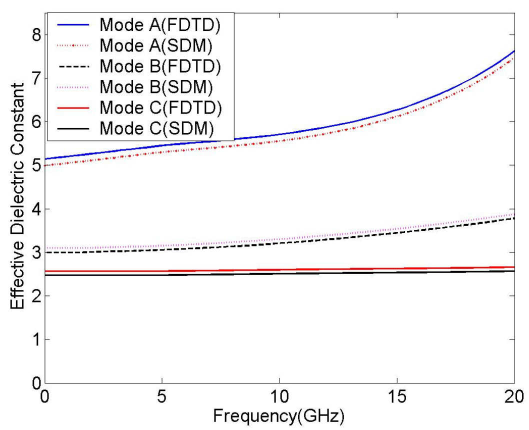


그림 5. 유효유전 상수(case 1)
Fig. 5. Effective dielectric constant for case 1.

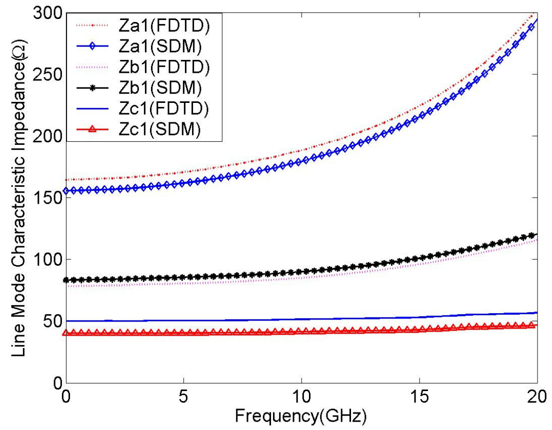


그림 6. 선로 모드 특성 임피던스(case 1)
Fig. 6. Line-mode characteristic impedance for case 1.

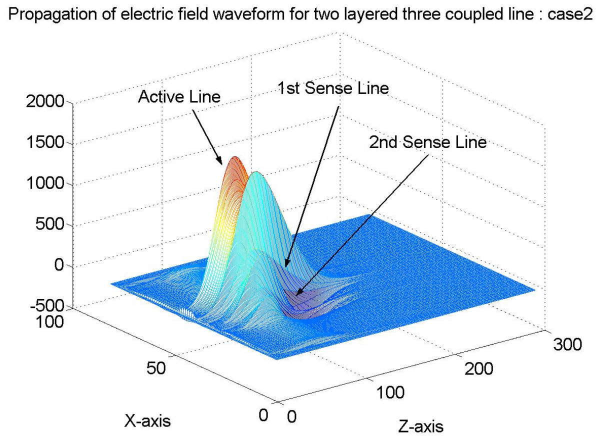


그림 7. 도체선을 따라 나타나는 전기장 파형(case 2)
Fig. 7. Electric field waveform along the conductors for case 2.

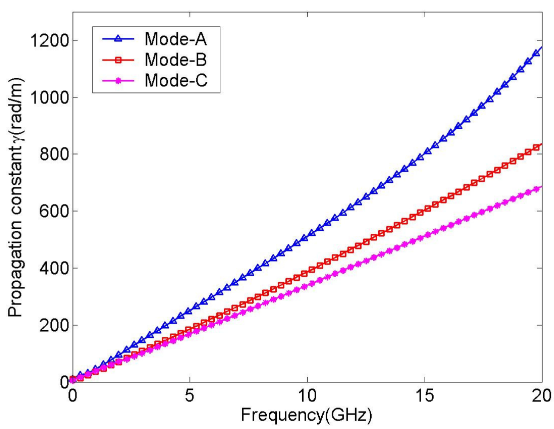


그림 8. 전파상수(case 2)
Fig. 8. Propagation constant for case 2.

conductor, L1=3000um, d=1000um, and L2=7000um in Figure 1, respectively.

Figures 3, 7 show electric field waveforms on the conductor lines in case 1, 2. And Figures 4-6 and Figure 8-10 show the variation of the effective dielectric constant, propagation constant and characteristic impedance for the symmetric and asymmetric three coupled line on the three-layered different substrates in case 1, 2 using the proposed normal mode approach and the FDTD technique.

In Figure 5 and 6, comparisons with a SDM(Spectral Domain Method) are also included. and they also agree very well. In most of simulations, two results for propagation constants, effective dielectric constants and characteristic impedances show negligible difference. In Figure 6, characteristic

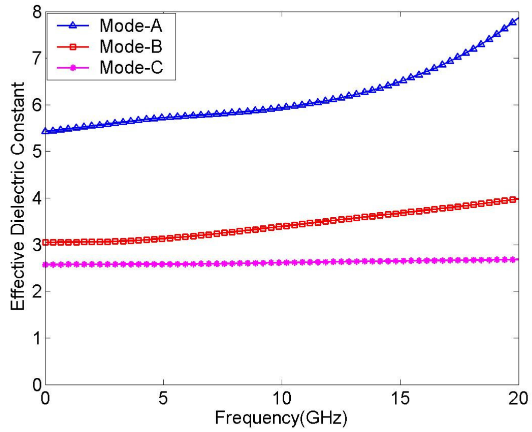


그림 9. 유효유전 상수(case 2)
Fig. 9. Effective dielectric constant for case 2.

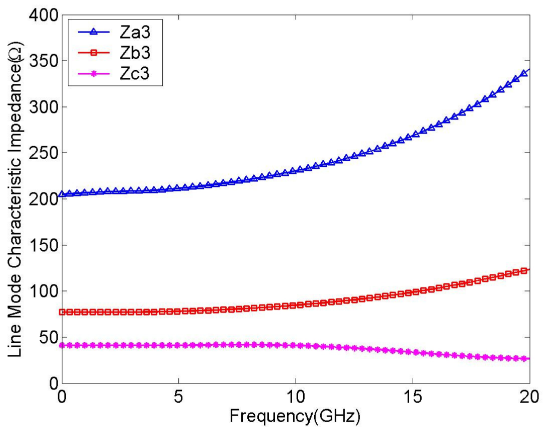


그림 10. 선로 모드 특성 임피던스(case 2)
Fig. 10. Line-mode characteristic impedance for case 2.

impedances using FDTD and SDM show 9Ω difference at DC for Mode C. Although it consumes more time or requires more memory space for simulation, this difference can be reduced if the grid spacing is decreased in simulation setting. From this, the rest of results are supposed to agree with conventional simulation results.

Therefore, proposed FDTD technique for the characterization of symmetric and asymmetric multiple coupled lines provides useful data or broadband frequency propagation characteristics in one time simulation.

V. CONCLUDING REMARKS

In this research, the full-wave Finite-Difference Time-Domain (FDTD) method for the computation of all the frequency-dependent characteristics of general asymmetric coupled lines in a multilayer substrate structure has been presented. Especially, asymmetric three coupled line embedded conductor structures on the two different substrate structures are analyzed over the FDTD technique and normal mode parameter approach. Comparison with Spectral Domain Method are given, and they agree very well. Application of the FDTD technique for the characterization of the multiple coupled lines provides broadband frequency data in one time simulation. The results for all the frequency-dependent propagation characteristics should be very useful in the analysis and design of multiple coupled line structures on multi-layered substrate such as couplers, matching networks and filters.

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