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論　文

차폐된 단일, 결합 및 Edge-Offset 마이크로 스트립 구조의 주파수 의존특성

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Frequency-Dependent Characteristics of Shielded Single, Coupled and Edge-Offset Microstrip Structures

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要 約 Spectral domain에서 hybrid mode 분석과 Galerkin method를 사용하여 차폐된 단일, 결합 및 edge-offset 마이크로 스트립 구조의 분산특성을 고찰하였다. 진행방향의 스트립 전류에 대한 새로운 2개의 basis function이 제안되었으며 그들을 사용한 수치해의 수렴속도를 비교하였다. 결합 마이크로 스트립의 전류분포는 단일 마이크로 스트립의 전류분포로 부터 Fourier 변환의 shift theorem을 이용하여 얻었으며 off-centered 스트립의 분산에 대한 영향이 논의 되었다. 수치결과들은 여러가지 구조 parameter들을 포함하며 다른 유용한 data들과 비교한 결과 잘 일치함을 알 수 있었다.

ABSTRACT Dispersion characteristics of shielded single, coupled and edge-offset microstrip structures are investigated by using hybrid mode analysis with Galerkin's method in the spectral domain. Two new basis functions for the longitudinal strip current are proposed and convergence rates of the solutions for the basis functions are compared. Current distribution of the coupled line is obtaind from that of the single line by using shift theorem of the Fourier transform. In addition, effects of off-centered inner strip conductor on dispersion are also discussed. Numerical results include various structural parameters and are compared with other available data and good agreements are observed.

I. INTRODUCTION

Various methods of microstrip analysis may be largely devided into two groups; the one is quasi-static analysis and the other is full-wave analysis. In quasi-static analysis[1~3], pure TEM mode propagation is assumed and line characteristics are calculated from the electrostatic capacitance of the structure while in full-wave analysis, parameters of the structure are obtained by solving wave equations rigorously. At lower frequencies quasi-static approximation is adequate for designing circuits, however at higher frequencies this approach is not valid because the parameters

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of the microstrip begin to change as frequency. This dispersive characteristic of the microstrip is due to propagation of hybrid modes [4].

With the increasing use of the microstrip line circuits at higher frequencies, a number of workers have studied dispersion properties of the microstrip line. Singular integral equation approach [5], Fourier expansion method [6], moment method [7] and spectral domain techniques [8-10], and several other methods of analysis have been used to calculate dispersion properties of the microstrip line. Among those, the spectral domain technique has numerical efficiency, which is mainly due to the fact that solutions in the techniques are extracted from algebraic equations rather than from coupled infegral equations typically appearing in the conventional space domain approaches.

In this paper, hybrid mode formulation is used in the spectral domain to calculate dispersion properties of single, coupled and edge-offset microstrip in shielded enclosure. Several basis functions for the longtudinal strip current are considered and convergence rates of the solution for the basis functions are compared. They include two new functions that have not been used so far, which have a simpler Fourier transform than other basis functions.

II. FORMULATION OF THE PROBLEM

Fig. 1 shows the cross section of the shielded microstrip line to be analysed. First, the structure is assumed to be uniform and infinitely extended in the z direction. It is also assumed that strip thickness is negligible and all the conductors and dielectrics are lossless.

Modes existing in the structure are not pure TE or TM modes but hybrid modes. It is well known that hybrid field components can be expressed in terms of superposition of the TE and TM fields which are derivable from the corresponding scalar potential ϕ^e and ϕ^h. For instance

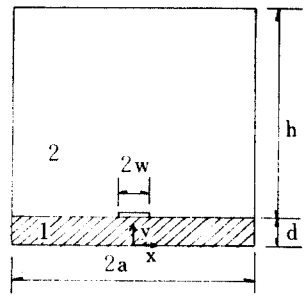

Fig 1 Shielded Microstrip Structure.

$$E_{zi} = j\frac{k_i^2-\beta^2}{\beta}\phi^e i(x, y)\,EXP(-j\beta z)$$
$$H_{zi} = j\frac{k_i^2-\beta^2}{\beta}\phi^h i(x, y)\,EXP(-j\beta z) \qquad (1)$$
$$k_1^2 = \omega^2\epsilon_0\mu_0\epsilon_r\mu_r$$
$$k_2^2 = \omega^2\epsilon_0\mu_0 = k_0^2$$

where, i=1, 2 designates each region and ω is operating frequency, β is unknown propagation constant, ϵ_0 and μ_0 is free space permittivity and permeability, respectively. The finite Fourier transforms of the scalar potentials are defined as

$$\tilde{\phi}^p i(n, y) = \int_{-a}^{+a}\phi^p i(x, y)\,EXP(j\hat{k}_n x)\,dx \qquad (2)$$
$$p = e \text{ or } h, \quad i = 1 \text{ or } 2$$

where, $\hat{k}_n$ is discrete Fourier transform variable defined by $(n-1/2)\pi/a$ for even mode, $n\pi/a$ for odd mode (n=1,2,......). In the spectral domain, the field quantities are now

$$\tilde{E}_{zi} = j\frac{k_i^2-\beta^2}{\beta}\tilde{\phi}^e i(n, y)\,EXP(-j\beta z)$$
$$\tilde{H}_{zi} = j\frac{k_i^2-\beta^2}{\beta}\tilde{\phi}^h i(n, y)\,EXP(-j\beta z) \qquad (3)$$

Other field components can be easily derived from the Maxwell's equations. Applying boundary conditions at y=0, d+h and continuity equations at y=d, some mathematical manipulations lead following coupled set of equations.

$$\tilde G_{11}(n,\beta)\tilde J_x(n)+\tilde G_{12}(n,\beta)\tilde J_z(n)=\tilde E_z(n)$$
$$\tilde G_{21}(n,\beta)\tilde J_x(n)+\tilde G_{22}(n,\beta)\tilde J_z(n)=\tilde E_x(n) \quad (4)$$

where

$$\tilde G_{11}=\tilde G_{22}=\hat{k}_n\beta\,(\gamma_2\tanh\gamma_2 h+\mu_r\gamma_1\tanh\gamma_1 d)/\det$$
$$\tilde G_{12}=[(\epsilon_r\mu_r k_0^2-\beta^2)\gamma_2\tanh\gamma_2 h+\mu_r(k_0^2-\beta^2)\gamma_1\tanh\gamma_1 d]/\det$$
$$\tilde G_{21}=[(\epsilon_r\mu_r k_0^2-\hat{k}_n^2)\gamma_2\tanh\gamma_2 h+\mu_r(k_0^2-\hat{k}_n^2)\gamma_1\tanh\gamma_1 d]/\det$$
$$\det=(\gamma_1\tanh\gamma_1 d+\epsilon_r\gamma_2\tanh\gamma_2 h)(\gamma_1\coth\gamma_1 d+\mu_r\gamma_2\coth\gamma_2 h)$$
$$\gamma_1^2=\hat{k}_n^2+\beta^2-\epsilon_r\mu_r k_0^2$$
$$\gamma_2^2=\hat{k}_n^2+\beta^2-k_0^2$$

where, $\tilde G_{11}(n,\beta)-\tilde G_{22}(n,\beta)$ are actually the Fourier transforms of dyadic Green's function components, and $\tilde J_z(n)$, $\tilde J_x(n)$ and $\tilde E_z(n)$, $\tilde E_x(n)$ are Fourier transforms of the longitudinal, transverse strip currents and electric fields, respectively. Equation (4) contains four unknowns so, in order to solve these equations Galerkin's method is applied in the spectral domain. The first step is to expand the unknown $\tilde J_z(n)$, $\tilde J_x(n)$ in terms of some known basis functions $\tilde J_{zm}(n)$, $\tilde J_{xm}(n)$;

$$\tilde J_z(n)=\sum_{m=1}^{N} d_m\tilde J_{zm}(n),\quad \tilde J_x(n)=\sum_{m=1}^{M} d_m\tilde J_{xm}(n) \quad (5)$$

where, cm, dm is unknown constant. The basis functions $\tilde J_{zm}(n)$, $\tilde J_{xm}(n)$ must be chosen that their inverse Fourier transforms are non zero only on the strip $|X|<W$. After substituting (5) into (4), and taking inner products of the resulting equations with the basis functions $\tilde J_{zi}(n)$, $\tilde J_{xi}(n)$ for different values of i, we obtain following matrix equations.

$$\sum_{m=1}^{M} K_{im}^{1,1} c_m+\sum_{m=1}^{N} K_{im}^{1,2} d_m=0 \quad i=1,2,\cdots,N$$
$$\sum_{m=1}^{M} K_{im}^{2,1} c_m+\sum_{m=1}^{N} K_{im}^{2,2} d_m=0 \quad i=1,2,\cdots,M \quad (6)$$

where,

$$K_{im}^{1,1}(\beta)=\sum_{n=1}^{\infty}\tilde J_{zi}(n)\tilde G_{11}(n,\beta)\tilde J_{xm}(n)$$
$$K_{im}^{1,2}(\beta)=\sum_{n=1}^{\infty}\tilde J_{zi}(n)\tilde G_{12}(n,\beta)\tilde J_{zm}(n)$$
$$K_{im}^{2,1}(\beta)=\sum_{n=1}^{\infty}\tilde J_{xi}(n)\tilde G_{21}(n,\beta)\tilde J_{xm}(n)$$
$$K_{im}^{2,2}(\beta)=\sum_{n=1}^{\infty}\tilde J_{xi}(n)\tilde G_{22}(n,\beta)\tilde J_{zm}(n) \quad (7)$$

In the derivation of right side of equation (6), *Parseval's theorem* is used because the electric fields and surface strip currents are orthogonal in the space domain, that is

$$\sum_{n=1}^{\infty}\tilde J_{zi}(n)\tilde E_x(n)=\frac{1}{2\pi}\int_{-a}^{+a} J_{zi}(x)E_x(x)\,dx=0$$

The simultaneous equation (6) is now solved for the propagation constant by setting determinant of coefficient matrix equal to zero and by seeking the roots of the resulting equation.

III. NUMERICAL COMPUTATION AND RESULTS

In the present method, the solution can be systematically improved by increasing the size of matrix (M+N), but the size of matrix can be held small if the first few basis functions are well chosen. Therefore choice of basis function is very important in this method. The results have been calculated for two choices of matrix size; 1) N=1, M=0 (zero-order approximation), 2) N=M=1 (first-order approximation). Since the differences between results of zero and first order approximation are very small, only zero-order results are plotted.

A. Single Microstrip Line

The dominant mode of the single line is lowest order Ez even-Hz odd (EHo) mode [16], which approaches quasi-TEM mode at lower frequency. For the dominant mode, following basis functions have been chosen for $J_{z1}(x)$ usually.

$$J_{z1}(X) = \frac{1}{\sqrt{1-(X/W)^2}}, \qquad \text{(a)}$$

$$\text{for } -W < X < W$$

$$= 0, \text{ otherwise}$$

$$J_{z1}(X) = \frac{1}{2W}\left[1+|X/W|^3\right] \qquad \text{(b)}$$

$$\text{for } -W < X < W$$

$$= 0, \text{ otherwise}$$

In this paper, two basis functions for the longitudinal strip current are proposed which have a simpler Fourier transform. Those are

$$J_{z1}(X) = \frac{1}{W}\,\mathrm{COSH}(KX/W), \qquad \text{(c)}$$

$$\text{for } -W < X < W$$

$$= 0, \text{ otherwise}$$

$$K : \text{some constant}$$

$$J_{z1}(X) = (X/W)^2 \qquad \text{(d)}$$

$$\text{for } -W < X < W$$

$$= 0, \text{ otherwise}$$

Fourier transform of (a) is known as zero-order Bessel function of first kind and Fourier transform of (b) is given in[7]. Now Fourier transforms of (c), (d) are given as follow

$$\tilde{J}_{z1}(n) = \frac{2W}{K^2+(\hat{k}_n W)^2} \cdot \left[\hat{k}_n W \sin(\hat{k}_n W)\cosh(K) + K\cos(\hat{k}_n W)\sinh(K)\right] \qquad \text{(c)}'$$

$$\tilde{J}_{z1}(n) = \frac{2}{\hat{k}_n^2 W}\left\{\hat{k}_n W \sin(\hat{k}_n W) + 2\cos(\hat{k}_n W) - \frac{2\sin(\hat{k}_n W)}{\hat{k}_n W}\right\} \qquad \text{(d)}'$$

Fig. 2, 3 shows the effective dielectric constant computed by above basis functions. The definition of the effective dielectric constant ϵ_{eff} is

$$\epsilon_{eff} = \left(\frac{\lambda_0}{\lambda_g}\right)^2 = \left(\frac{\beta}{k_0}\right)^2$$

The results indicate that one of the basis function proposed in this paper, COSH(KX/W) produces good agreements with results for Maxwell distribution function (a) (within 0.3 %) requiring less Fourier terms to obtain accuracy of 0.1 % result for including 300 Fourier terms in

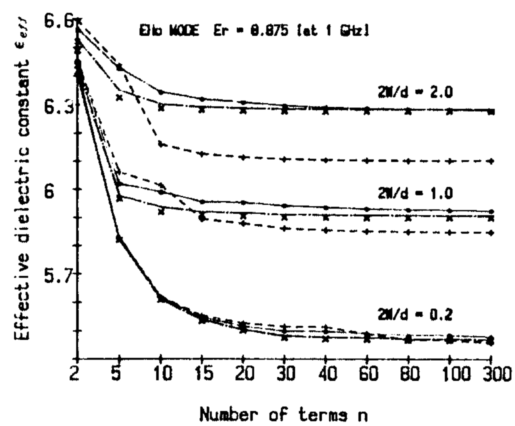

Fig 2 Convergence Rate for the Basis Functions.

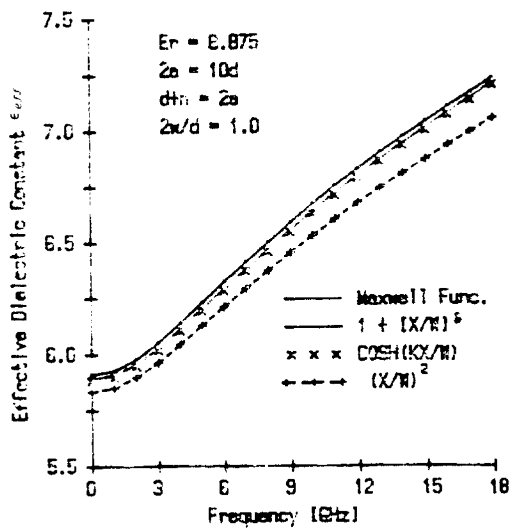

Fig 3 ϵeff versus frequency for the Basis Functions.

infinite series. Another basis function $(X/W)^2$ produces also good results in the ratio 2W/d = 0.2. However differences from the other data become serious when the ratio increases and convergence rates are relatively slow.

The effective dielectric constant. ϵ_{eff} approaches ϵ_r in the high frequency limit, indicating that at the high frequencies, all the energy tends to be confined in the dielectric substrate. Therefore the guided wavelength approaches the wavelength in the substrate material, and influences of shielding wall decrease as frequency increases. This result plotted in Fig. 4.

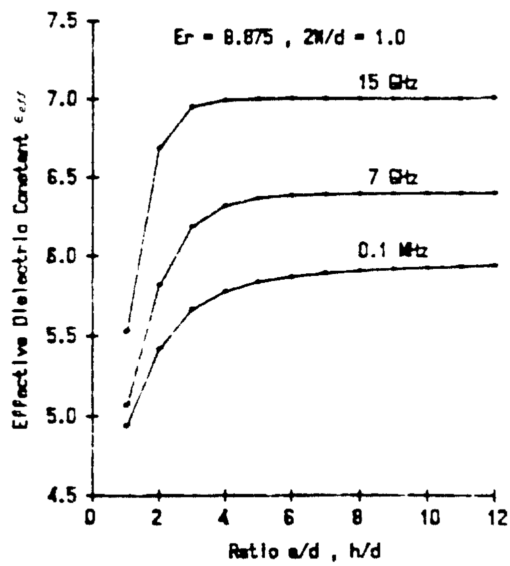

Fig 4 Influence of metallic enclosure.

B. Coupled Microstrip Line

A pair of coupled line (fig. 5) can support one even and one odd dominant mode. The current distribution of the coupled microstrip can be

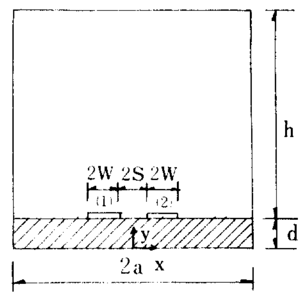

Fig 5 Coupled Microstrip Line.

obtained from that of the single microstrip. Let $\tilde{J}z(1)$ and $\tilde{J}z(2)$ refers to the Fourier transform of current distribution on the coupled line to the left of the origin (x=0) and right of the origin, respectively. Then with the time shift theorem of the Fourier transform we get

$$\tilde{J}_z(1) = EXP(-j\hat{k}_n(W+S))\,\tilde{J}_z(n),$$

$$\tilde{J}_z(2) = EXP(j\hat{k}_n(W+S))\,\tilde{J}_z(n)$$

$\tilde{J}_z(n)$: F.T of currunt distribution for the single microstrip.

In the even mode, the longitudinal currents on both strips are equal in magnitude while in the odd mode, they are equal in magnitude but opposite in phase. Therefore current distribution function of the coupled line $\tilde{J}zc(n)$ can be written as

$$\tilde{J}_z c(n) = [\delta EXP(-j\hat{k}_n(W+S)) + EXP(j\hat{k}_n(W+S))]\tilde{J}_z(n)$$

$\delta = +1$ for even mode

$\quad 1$ for odd mode

Numerical results for coupled microstrip line are plotted in fig. 6 with those of Krage and Haddad[6]. It is seen that two results are well agreed, especially in odd mode case. However there are 1 % differences between the two results in even mode case, these differences may be reduced by increasing the size of matrix but additive computation time is required.

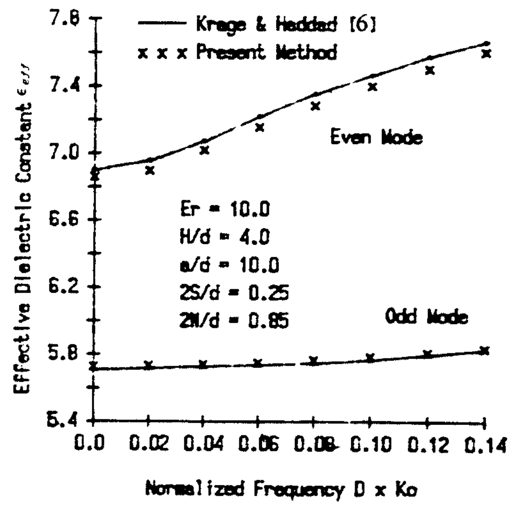

Fig 6 Even and Odd Mode Characteristics of the Coupled Microstrip Line.

Fig. 7 shows frequency dependence of coupled microstrip line with varying spacing between strips. It is also found that increasing spacing increases dispersion in odd mode but non-monotonical behaviors are presented in even mode. And

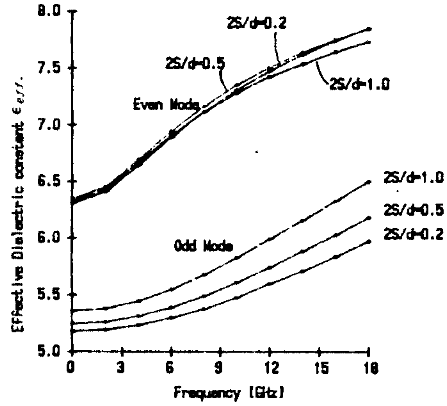

Fig 7 Changes of ϵ_{eff} with Varying Spacings ϵr= 8.875, 2a=10d, d+h=2a, 2w/d=1, d=1.27 mm).

coupled line propagating with even mode has more dispersive character.

C. Edge-Offset Structure

If the strip conductor of the single line is displaced from the center(x=0), it refers to edge-offset microstrip structure. Fig. 8 shows a edge-offset structure which has a displaced strip by dS to the side wall. The field distributions of this structure can be thought as odd mode case of coupled microstrip line having same dielectric media and two times of dimension in a because of electric wall formed between strips. Therefore it is expected that propagation constant of the edge-offset structure decreases as displacement (dS) increases.

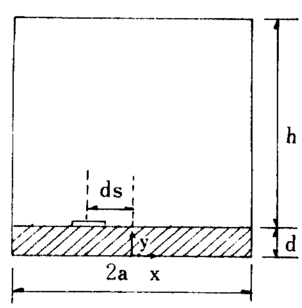

Fig 8 Edge-offset Microstrip structure.

Calculated results are compared with[3], which based on quasi-static approximation. It can be shown that two results are agreed well at low frequency in fig. 9.

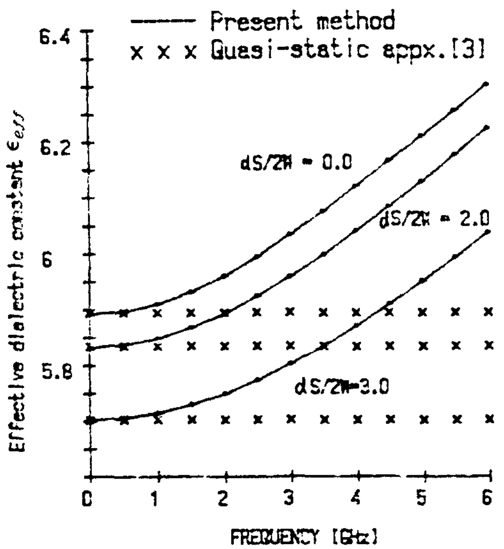

Fig 9 Effects of Off-Centered strip Conductor.

Finally, half interval search and method of false position are used in all root searching procedures and polynomial approximations[18] are used to estimate zero-order Bessel functions of first kind. Typical computation time was about 0.8s/point for single microstrip, 1.2 s/point for coupled microstrip on Cyber 170/825 system when COSH(KX/W) was used to zero-order approximation.

IV. CONCLUSION

Frequency dependent characteristics of shielded single, coupled and edge-offset microstrip lines are investigated by using hybrid mode analysis with Galerkin's method in the spectral domain. Of the two proposed basis functions, COSH (KX/W) produced good results and less Fourier terms are required than other basis functions for given accuracy. It is found that coupled line propagating with even mode presents more dispersive character and metallic enclosure does not affect to the effective dielectric constant when the ratio a/d, h/d greater than 4~5 at high frequency (above 15GHz). Although numerical computations in this paper restricted to the dominant mode only, high order mode solution can be obtained by replacing basis functions for specific mode of interest. It is expected that these results are useful for MIC (Microwave Integrated Circuits) design at high frequencies.

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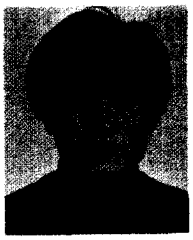

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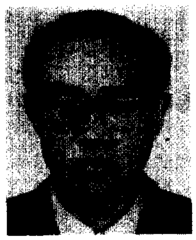

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