PLANAR TRANSMISSION LINES WITH FINITELY THICK CONDUCTORS AND LOSSY SUBSTRATES

T. Kitazawa, C. W. Kuo**, K.-S. Kong** and T. Itoh***

** Department of Electronic Engineering, Kitami Institute of Technology, Kitami, 090 Japan*

*** Department of Electrical Engineering, University of California, Los Angeles, Los Angeles, CA90024*

ABSTRACT

Various types of lossy planar transmission lines are analyzed by extending the spectral domain approach. Introduction of the finite metallization model and choice of the proper basis functions for the model does not only overcome the computational difficulty, but also reduce drastically the computation labor for the calculation of the conductor loss. This procedure preserves the versatility of SDA, and it can be applied to various types of planar transmission lines. Numerical results include the effective dielectric constants, characteristic impedances and total losses (conductor and dielectric losses) for slot lines, coplanar waveguides, and strip lines. Numerical computations show that the currents on the side walls of the metal conductors make the considerable contributions to the conductor loss and cannot be neglected, and that the quasistatic approximation gives reasonable results for the loss calculation of CPW if the metallization thickness effect is taken into consideration properly.

I. INTRODUCTION

The spectral domain approach (SDA)[1] has been successfully applied to analyze the propagation characteristics of various types of lossless planar transmission lines [2]-[10]. At first, SDA formulation was based on the the assumption of the "zero thickness perfect conductor". The effect of the finite metallization thickness is taken into consideration by authors for lossless slot lines[4], coplanar waveguide[2],[7] and strip lines[10]. For the lossy transmission lines with imperfect conductors, attenuation have been evaluated based on the perturbational scheme with the assumption that the metallization thickness is zero[8],[11]. However, calculations based on the zero-thickness conductor cause a computational difficulty, in which the power lost in the conductor is not principally integrable[8],[12],[13].

The spectral domain approach is extended here to analyze the planar transmission lines with lossy media. Introduction of the finite metallization model and choice of the proper basis functions for this model overcomes the computational difficulty without any approximations. Also, the use of the orthogonality relation of the modes reduces the computation labor drastically. This procedure preserves the versatility of SDA, and it can be applied to various types of planar transmission lines with finitely thick conductors.

II. ANALYTICAL FORMALISM

The general structure of planar transmission lines consists of a number of printed conductors of finite thickness with the stratified media (Fig.1). One or more of these layers may be anisotropic, e.g., uniaxial dielectrics[5] or gyrotropic materials[14]. At first, those layers as well as metal conductors are assumed to be lossless, and the extended spectral domain approach[10],[14] are utilized for the formulation. Following the procedure in [10],[14], the electromagnetic fields in the subregion (m) are expressed in terms of the aperture fields at $y = t$, $e_i^U(x)$, and at $y = 0$, $e_i^L(x)$,

$$E^{(m)}(x,y,z) = \sum_i \int_y \{\overline{\overline{T}}_{Ui}(x,y|x')e_i^U(x') + \overline{\overline{T}}_{Li}(x,y|x')e_i^L(x')\}\, dx'\, e^{-j\beta z}$$

$$H^{(m)}(x,y,z) = \sum_i \int_y \{\overline{\overline{Y}}_{Ui}(x,y|x')e_i^U(x') + \overline{\overline{Y}}_{Li}(x,y|x')e_i^L(x')\}\, dx'\, e^{-j\beta z} \quad (1)$$

where β is the phase constant and the $\overline{\overline{T}}$'s and $\overline{\overline{Y}}$'s are the dyadic Green's functions.

Attenuation due to imperfect conductors and dielectrics is accounted for by the perturbational procedure. Losses due to the imperfect conductor and dielectric are determined by

$$\alpha_c = \frac{P_C}{2P_0} \quad \text{and} \quad \alpha_d = \frac{P_d}{2P_0} \quad (2)$$

respectively. P_0 is the average power flow, and P_C and P_d are the power lost in the conductors and the dielectrics. They are given by

$$P_C = \frac{1}{2} R_s \int_C |H_t|^2\, dl \qquad P_d = \frac{1}{2}\omega\varepsilon \tan\delta \int_{S_d} |E|^2\, dS \quad (3)$$

where E and H are the electromagnetic fields for the lossless case (1).

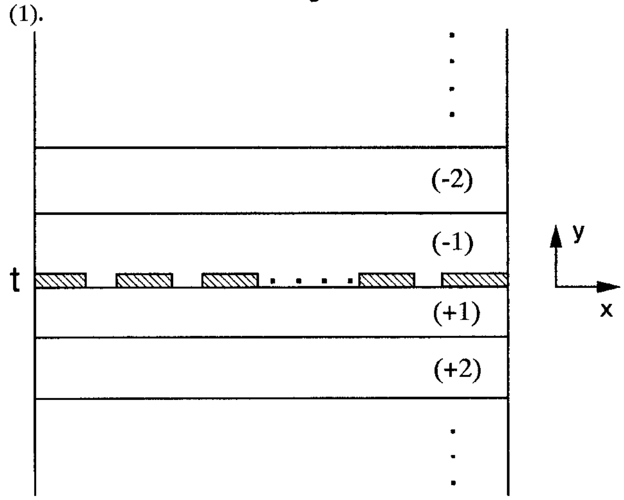

Fig.1 General structure of planar transmission lines

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III. NUMERICAL PROCEDURE

The unknown aperture fields $e_i^U(x)$, $e_i^L(x)$ are expanded in terms of the appropriate basis functions. For the planar transmission lines, the following basis functions were proposed by the authors[2],[4],[5];

$$f_{xk}(x) = \left[1-\left\{\frac{2(x-c)}{W}\right\}^2\right]^{-\frac{1}{2}} T_k\left\{\frac{2(x-c)}{W}\right\}$$
$$f_{zk}(x) = U_k\left\{\frac{2(x-c)}{W}\right\} \qquad (4)$$

where $T_k(x)$ and $U_k(x)$ are Chebyshev's polynomials of the first and second kind, respectively. This set of basis functions incorporate the singularities near the edge of the zero-thickness conductor (the fields have $\delta^{-1/2}$ variation near edge). This set of basis functions gives fast convergence, and accurate results have been obtained for lossless planar transmission lines with zero as well as finite metallization thickness[2], [4],[5],[10],[14]. However, when the fields expressed in terms of this set of basis functions are used to calculate conductor loss by the perturbation scheme (3), the resulting integrand contains a pole of the first order at the edge[13]. In the conventional methods, which neglect the metal conductor thickness, the integrals were terminated at a definite distance just short of the edge[8],[12] to avoid this divergence.

The following basis functions are used in the computations here :

$$f_{xk}(x) = \left[1-\left\{\frac{2(x-c)}{W}\right\}^2\right]^{-\frac{1}{3}} C_{2k}^{1/6}\left\{\frac{2(x-c)}{W}\right\}$$
$$f_{zk}(x) = \left[1-\left\{\frac{2(x-c)}{W}\right\}^2\right]^{\frac{2}{3}} C_{2k-1}^{7/6}\left\{\frac{2(x-c)}{W}\right\} \qquad (5)$$

where $C_k^{\mu}(x)$ are Gegenbauer polynomials. Basis functions (5) represent the actual field variations more properly near the edge of the conductor of finite-thickness by exhibiting $\delta^{-1/3}$ variations for the transverse components of electric fields and $\delta^{2/3}$ for the longitudinal components of electric fields[15]. The introduction of the finite thickness of the metallization and the basis functions appropriate to this model makes (3) integrable. However, the direct evaluation of the integration over the conductor should be avoided, because it requires the x-integral of the infinite summation or integral in eq.(3). Instead we rewrite the integral as (Fig.2)

$$\int_{x_0}^{x_1} |H_t(t+0)|^2 dx + \int_{x_2}^{x_3} |H_t(t+0)|^2 dx = \int_{x_0}^{x_3} |H_t(t+0)|^2 dx - \int_{x_1}^{x_2} |H_t(t-0)|^2 dx \qquad (6)$$

The orthogonality relation of the modes in each region can be utilized on the right hand side and the integrals reduce to the single integrals or summations. This procedure reduces the computational labor required for the conductor loss calculation drastically (e.g. double integrals become single integrals).

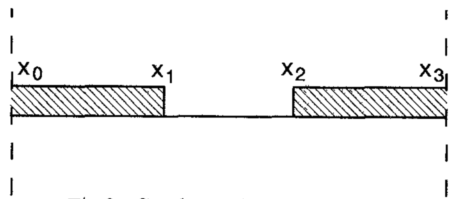
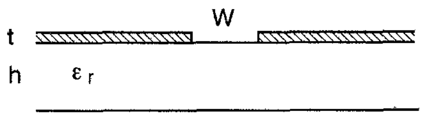


Fig.2 Conductor loss calculation



conductor ; $\sigma = 4.1\times10^7$ S/m , $t = 6\ \mu m$

dielectrics ; $\varepsilon_r = 9.8$, $\tan\delta = 0.0002$, $h = 0.635$ mm

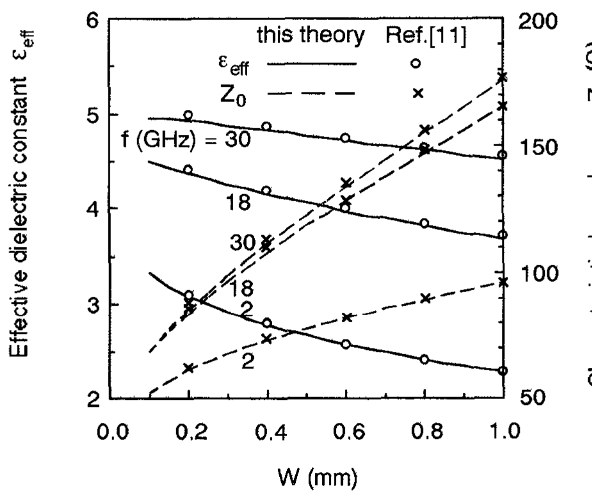


Fig.3 (a) Effective dielectric constant and characteristic impedance of slot line

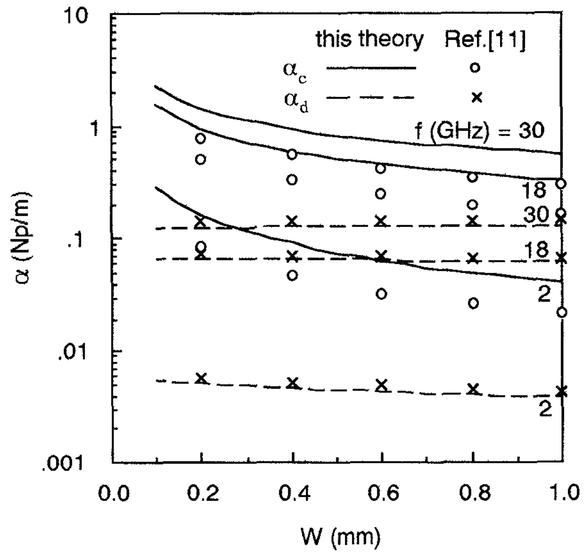


Fig.3 (b) Conductor and dielectric losses of slot line

IV. RESULTS

Fig.3 (a) and (b) show the effective dielectric constant $\varepsilon_{eff} = (\beta/\omega\sqrt{\varepsilon_0\mu_0})^2$, the characteristic impedances Z_0 and the conductor and dielectric losses for slot line together with the published data[11]. The metal conductor thickness is neglected in [11], while its thickness is chosen 6 μm in this work. Close agreement is observed in the effective dielectric constant ε_{eff}, the characteristic impedances Z_0 and the dielectric loss α_d calculations. However, the conductor loss values α_c are larger than those in [11]. If the current on the side walls ($t > y > 0$) of the metal conductors is neglected, then our values become comparable with values of [11].

Fig.4 (a) and (b) show the effective dielectric constant and the total (conductor and dielectric) losses for symmetrical coplanar waveguide (CPW). The quasistatic approximation has given reasonable results for the line parameters of the lossless CPW in the lower frequency range[6],[7]. The quasistatic value of ε_{eff} by the method in [7] is presented for comparison (Fig.4 (a)). In the quasistatic approximation, the incremental inductance formula[16] can be utilized for evaluating the conductor loss. The incremental increase in the inductance caused by the incremental recession of conductor surfaces (Fig.5) is calculated numerically. The quasistatic total losses calculation gives reasonable results for wide range of parameters for CPW (Fig.4 (b)).

Fig.6 shows the effective dielectric constant and the total (conductor and dielectric) losses for shielded strip line. The quasistatic values are presented for comparison. However, in strip lines, the frequency dependence is much larger than that in CPW, and the quasistatic approximation gives reasonable results only in the lower frequencies.

V. CONCLUSIONS

Lossy planar transmission lines are analyzed by extending the spectral domain approach combined with the perturbation method. Introduction of the finite metallization model and choice of the proper basis functions for the model overcomes the computational difficulty. Also the computation labor is reduced by using the orthogonality relation of the modes. The effective dielectric constants, characteristic impedances and total losses (conductor and dielectric losses) are calculated for slot lines, coplanar waveguides, and strip lines. Numerical computations show that the currents on the side walls of the metal conductors make the considerable contributions to the conductor loss and cannot be neglected, and that the quasistatic approximation gives reasonable results for the loss evaluation of coplanar waveguide if the metallization thickness effect is taken into consideration properly.

ACKNOWLEDGEMENT

This work was supported by the Army Research Office under contract number DAAL03-88-K-0005.

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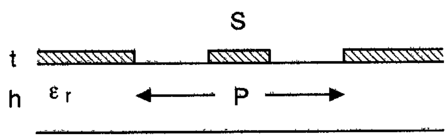

conductor ; $\sigma = 4.1\times10^7$ S/m , $t = 3$ μm , $P = 0.3$ mm

dielectrics ; $\varepsilon_r = 12.9$, $\tan\delta = 0.0003$, $h = 0.1$mm

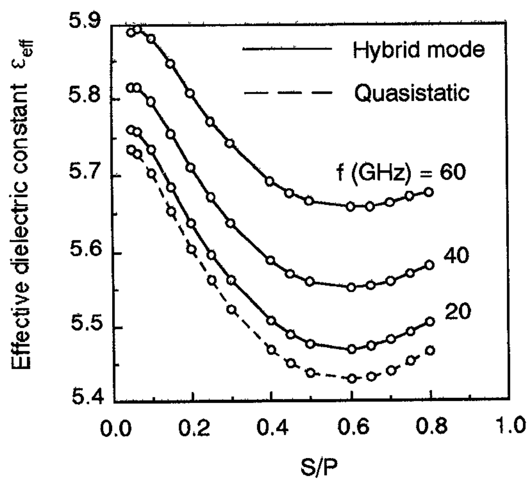

Fig.4 (a) Effective dielectric constant of CPW

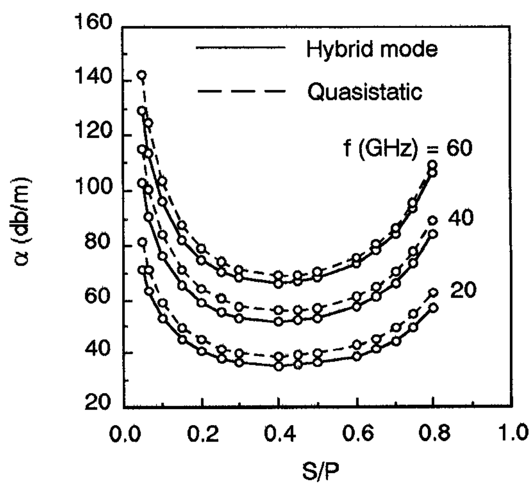

Fig.4 (b) Total losses of CPW

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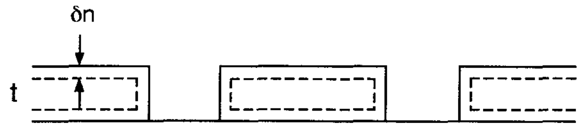
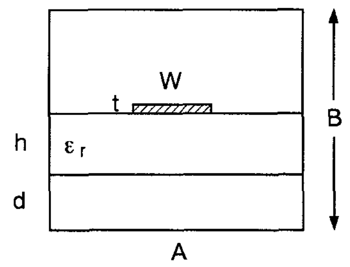


Fig.5 Recession of conductor surfaces



dielectrics ; ε_r= 12.9 , tan δ = 0.0003 , h = 0.25 mm

conductor ; $\sigma = 4.1\times10^7$ S/m , t = 6 μm , W = 0.3 mm

A = 1.27 mm , B = 2.54 mm

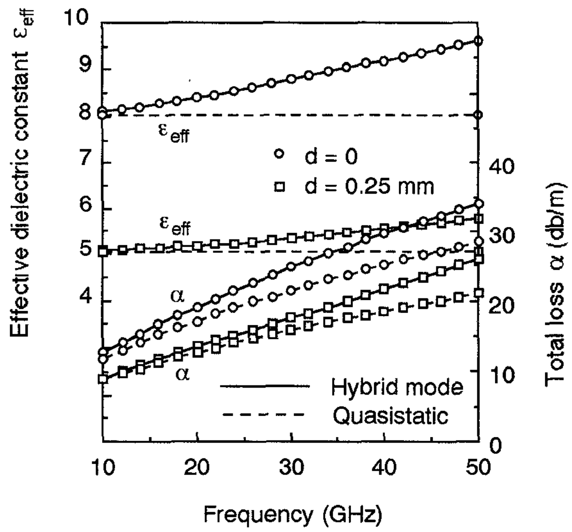


Fig.6 Propagation characteristics of shielded strip line