Metallization Thickness Effect of Striplines with Anisotropic Media: Quasi-Static and Hybrid-Mode Analysis

TOSHIHIDE KITAZAWA, SENIOR MEMBER, IEEE

Abstract —**The effect of metallization thickness in striplines is investigated on the basis of the quasi-static and frequency-dependent hybrid-mode formulations. The formalism utilizes the aperture fields as source quantities and employs the extended version of the network analytical methods of electromagnetic fields. It is therefore applicable for the general structure, i.e., coupled thick strips with uniaxially anisotropic media. Numerical computations include comparisons with available data for the simpler cases to show the accuracy of the present method and the quasi-static and frequency-dependent hybrid-mode solutions for single and coupled thick strips with anisotropic media.**

I. INTRODUCTION

GALERIKIN'S procedure used in the spectral domain has been successfully applied to analyze the propagation characteristics of striplines [1] and continues to hold the premier position among the numerical methods. Accurate numerical values are available for both the quasi-static and the frequency-dependent hybrid-mode characteristics for cases with isotropic and/or anisotropic media [2]–[12]. However, most of them have been based on the assumption that the strip conductors have zero thickness. It is evident that the effect of metallization thickness becomes more serious in the higher frequency range, and it will not be possible to neglect it in millimeter-wave integrated circuits, where the cross-sectional dimensions are so small and the relative thickness of the metallization becomes significant. The finite conductor thickness has been introduced into the spectral-domain approach by authors for coplanar types of transmission lines such as slot lines [13], finlines [14], and CPW [15].

This paper presents an analytical method for the shielded strips of finite metallization thickness. The method is based on a unified procedure for the quasi-static (stationary) and frequency-dependent hybrid-mode solutions, and the formalism, which is developed in the spectral domain and based on the extended version of the network analytical methods of electromagnetic fields [7], [13], [14], is applicable for the general structure, i.e., coupled thick strips with uniaxially anisotropic media. Numerical examples obtained by the accurate computational method include comparisons with available data for the simpler cases and the quasi-static and frequency-dependent hybrid-mode characteristics for single and coupled striplines with anisotropic media, showing the effect of metallization thickness. Included in the results presented here for the first time are the different frequency-dependent effects of metallization thickness in striplines compared with those in coplanar-type transmission lines and the difference in the metallization thickness effect between the effective dielectric constant and the characteristic impedance and that between the even- and odd-mode cases of coupled striplines.

Manuscript received June 17, 1988; revised October 28, 1988. This work was supported by the SANEYOSHI Scholarship Foundation and by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science and Culture, Japan.

The author is with the Department of Electronic Engineering, Kitami Institute of Technology, Kitami, 090 Japan.

IEEE Log Number 8826050.

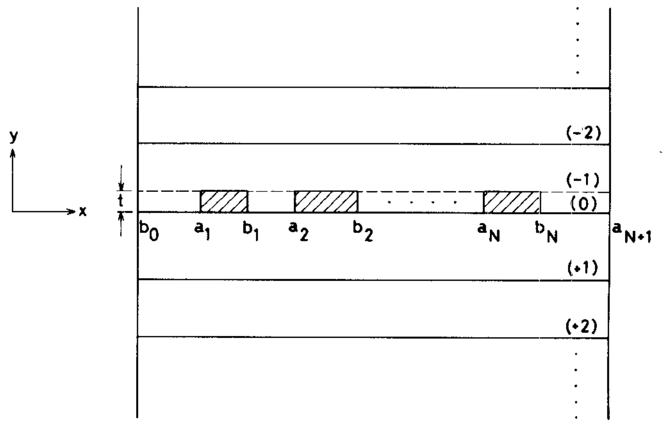

Fig. 1. General structure of striplines with finite metallization thickness.

II. THEORY

A. Network Analytical Formalism of Electromagnetic Fields

Fig. 1 shows the cross section of thick-strip conductors with stratified uniaxially anisotropic media. The permittivity of the region (m) is given by

$$\bar{\bar{\epsilon}}^{(m)} = \left(\hat{x}_0 \epsilon_{\perp}^{(m)} \hat{x}_0 + \hat{y}_0 \epsilon_{\parallel}^{(m)} \hat{y}_0 + \hat{z}_0 \epsilon_{\perp}^{(m)} \hat{z}_0 \right) \epsilon_0 \qquad (m = 0, \pm 1, \pm 2, \cdots). \quad (1)$$

The conventional analytical methods for striplines of zero thickness, which are based on the spectral-domain approach and use the charge or the current densities on the strip conductors, cannot be applied to the thick-strip case

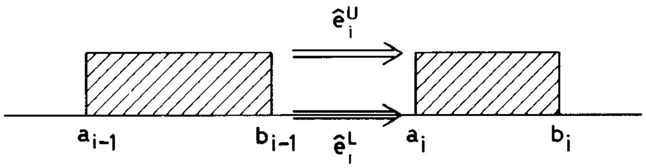

Fig. 2. Aperture fields as source quantities.

considered here. In the following, the aperture fields (Fig. 2) are used as source quantities, and the network analytical methods for electromagnetic fields [14] will be extended. The electromagnetic fields in the region (m) can be expressed as

$$\left.\begin{matrix}\hat{E}^{(m)}(x,y,z)\\ \hat{H}^{(m)}(x,y,z)\end{matrix}\right\} = \sum_{l=1}^{2}\sum_{n=0}^{\infty}\left\{\begin{matrix}V_{ln}^{(m)}(y)\hat{f}_{ln}^{(m)}(x)\\ I_{ln}^{(m)}(y)\hat{g}_{ln}^{(m)}(x)\end{matrix}\right\} e^{-j\beta z} \qquad (m=0,\pm1,\pm2,\cdots) \quad (2)$$

where the vector mode functions $\hat{f}$ and $\hat{g}$ in each region are given as follows. For $y > t$ and $0 > y$ $(m = \pm1, \pm2,\cdots)$,

$$\hat{f}_{1n}^{(m)}(x) = \frac{1}{K_0}\cdot\frac{\alpha_n}{W_0}\cdot\{\hat{x}_0\alpha_n\cos\alpha_n(x-b_0)+\hat{z}_0 j\beta\sin\alpha_n(x-b_0)\}$$

$$\hat{f}_{2n}^{(m)}(x) = \frac{1}{K_0}\cdot\frac{\alpha_n}{W_0}\cdot\{\hat{x}_0 j\beta\cos\alpha_n(x-b_0)+\hat{z}_0\alpha_n\sin\alpha_n(x-b_0)\}$$

$$\alpha_n = \frac{n\pi}{W_0} \qquad K_0 = \sqrt{\alpha_n^2+\beta^2} \qquad (3)$$

$$W_0 = a_{N+1} - b_0.$$

For $t > y > 0$ and $b_{i-1} < x < a_i$,

$$\hat{f}_{1n}^{(0)}(x) = \frac{1}{K_i}\cdot\frac{\alpha_n}{W_i}\cdot\{\hat{x}_0\alpha_n\cos\alpha_n(x-b_{i-1}) + \hat{z}_0 j\beta\sin\alpha_n(x-b_{i-1})\}$$

$$\hat{f}_{2n}^{(0)}(x) = \frac{1}{K_i}\cdot\frac{\alpha_n}{W_i}\cdot\{\hat{x}_0 j\beta\cos\alpha_n(x-b_{i-1}) + \hat{z}_0\alpha_n\sin\alpha_n(x-b_{i-1})\}$$

$$\alpha_n = \frac{n\pi}{W_i} \qquad K_i = \sqrt{\alpha_n^2+\beta^2} \qquad (4)$$

$$W_i = a_i - b_{i-1}$$

$$\hat{g}_{ln}^{(m)}(x) = \hat{y}_0 \times \hat{f}_{ln}^{(m)}(x) \qquad (5)$$

where β is the phase constant. The mode voltages $V_{ln}^{(m)}(y)$ and currents $I_{ln}^{(m)}(y)$ in (2) can be derived by applying conventional circuit theory to the equivalent circuits in the y direction [14] (Fig. 3) The mode voltages and currents are substituted into (2), and the electromagnetic field representations in the regions of Fig. 1 can be expressed in terms of

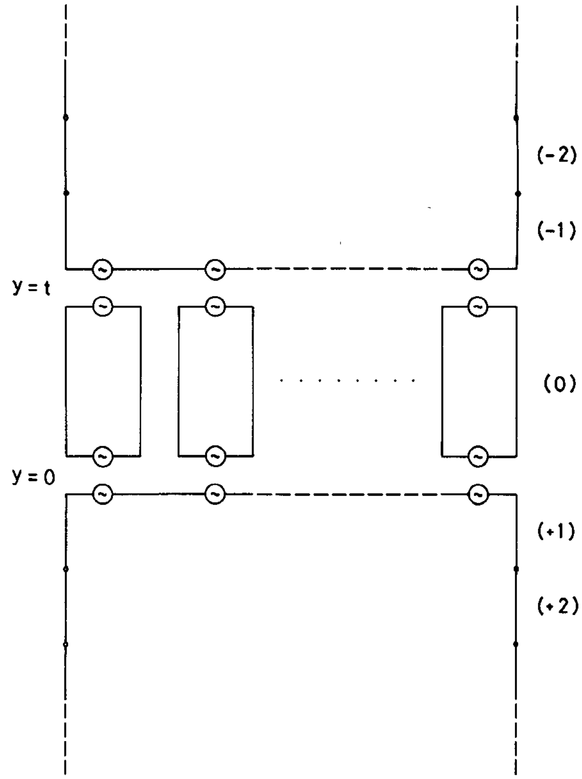

Fig. 3. Equivalent circuits for transverse section of striplines with the finite metallization thickness of Fig. 1.

aperture fields at $y = t$, $\hat{e}_k^U(x)$ and at $y = 0$, $\hat{e}_k^L(x)$:

$$\hat{E}^{(m)}(x,y,z) = \sum_{i=1}^{N+1}\int_x\int_y\{\bar{\bar{T}}_U^{(m)}(x,y|x',y')\cdot\hat{e}_i^U(x')\delta(y'-t)+\bar{\bar{T}}_L^{(m)}(x,y|x',y')\cdot\hat{e}_i^L(x')\delta(y')\}\cdot dy'\,dx'\,e^{-j\beta z} \qquad (6)$$

$$\hat{H}^{(m)}(x,y,z) = \sum_{i=1}^{N+1}\int_x\int_y\{\bar{\bar{Y}}_U^{(m)}(x,y|x',y')\cdot\hat{e}_i^U(x')\delta(y'-t)+\bar{\bar{Y}}_L^{(m)}(x,y|x',y')\cdot\hat{e}_i^L(x')\delta(y')\}\cdot dy'\,dx'\,e^{-j\beta z} \qquad (7)$$

where the $\bar{\bar{T}}$'s and $\bar{\bar{Y}}$'s are the dyadic Green's functions. The above expressions are rigorous, i.e., no approximations for simplification have been introduced in the derivation, and both the simple quasi-static and the rigorous hybrid-mode analysis will be developed by using the field representations (6) and (7).

B. Quasi-Static Analysis

For the quasi-static characteristics of the strips of zero thickness, where the charge distributions on the strip conductors are source quantities, the variational expressions have been derived for the inverse of the capacitance for single or symmetrical two-coupled strips [7]. For multiply coupled strips [12] the expressions have been derived for the compliance matrix, which is the inverse matrix of the capacitance matrix. Then the quasi-static characteristics, i.e., the phase constants β_k and characteristic impedances Z_{ik}, have been described in terms of the capacitances or the capacitance matrices of the cases with and without substrates [7], [12].

On the contrary, as for thick strip conductors considered here, the aperture fields play a fundamental role instead of the charge distributions, and the quasi-static characteristics are described in terms of the capacitance matrices, which are defined as

$$Q = CV \tag{8}$$

where the transposes of Q and V are

$$Q^T = [Q_1, Q_2, \cdots, Q_N] \tag{9}$$

$$V^T = [V_1, V_2, \cdots, V_N]. \tag{10}$$

Here Q_i is the total charge on the ith strip and V_i is the potential of the ith strip conductor. The elements of the capacitance matrix $[C]_{ij}$ are derived in the stationary expression.

We consider the following excitation:

$$V_i \neq 0 \qquad V_j = 0 \qquad (j \neq i) \tag{11}$$

to determine the diagonal elements $[C]_{ii}$. Under this excitation condition, the capacitance $[C]_{ii}$ can be related to the electrostatic energy stored per unit length, U, by

$$[C]_{ii} = \left.\frac{2U}{V_i^2}\right|_{V_j=0}. \tag{12}$$

U can be calculated by applying the quasi-static approximation, namely $\omega \to 0$ and $\beta \to 0$, to the electric field representation (6):

$$U = \frac{1}{2}\int (\hat{D}\cdot\hat{E})\, dy\, dx. \tag{13}$$

Also, the potential of the ith strip conductor V_i can be obtained by

$$V_i = \sum_p \int e_{px}^U(x)\, dx = \sum_p \int e_{px}^L(x)\, dx \tag{14}$$

where e_{px}^U and e_{px}^L are the x components of the upper and lower aperture fields, $\hat{e}_p^U$ and $\hat{e}_p^L$, respectively. Equation (12) has a stationary property and it places an upper bound on the exact value of $[C]_{ii}$, whereas the conventional methods for striplines of zero thickness, which have used the charge density on the strip conductor as the source quantity, provide a lower bound for $[C]_{ii}$. Both the lower and the upper bound calculation for the zero-thickness case will be carried out to clarify the margin of error.

The off-diagonal elements $[C]_{ij}$ can be obtained by considering the following excitation:

$$V_i = V_j \neq 0 \qquad V_k = 0 \qquad (k \neq i, j) \tag{15}$$

and using a procedure analogous to that applied for $[C]_{ii}$.

C. Hybrid-Mode Analysis

Applying the continuity conditions at the aperture planes $y = t$ and 0 to the integral representations of the magnetic fields (7), we obtain the integral equations on the aperture fields $\hat{e}_p^U(x)$ and $\hat{e}_p^L(x)$ and, implicitly, the propagation constant β. Then, applying Galerkin's procedure to the integral equations, we obtain the determinantal equation for β.

The conventional formulation procedure, which is based on the current on the strip conductor, is possible only for the strips of zero thickness, and it gives the integral equation on the current density $\hat{i}(x)$. Numerical computations based on the current density will be carried out for the zero-thickness case and will be compared with the values based on the aperture fields.

III. Numerical Examples

Special care should be taken to obtain accurate numerical calculations because the aperture fields, i.e., source quantities, must approximate a wider region for the usual strip cases than the charge and current distributions, and because the effect of the strip conductor thickness consists of only a fraction of the propagation characteristics. The effect of the metallization thickness can be estimated by accurate numerical procedures, such as the Ritz and Galerkin methods. In these numerical computations, the unknown quantities $\hat{e}_i^U(x)$ and $\hat{e}_i^L(x)$ are expanded in terms of appropriate basis functions. Taking the edge effect into consideration, the following basis functions are chosen:

$$\frac{T_k\left\{\dfrac{2(x-S_i)}{W_i}\right\}}{\sqrt{1-\left\{\dfrac{2(x-S_i)}{W_i}\right\}^2}},$$

$$S_i = (a_i + b_{i-1})/2; \qquad W_i = a_i - b_{i-1} \tag{16}$$

for the x components of the aperture fields, and

$$U_k\left\{\frac{2(x-S_i)}{W_i}\right\} \tag{17}$$

for the y components, where $T_k(x)$ and $U_k(x)$ are Chebyshev polynomials of the first and second kinds, respectively. For the apertures at both ends (contiguous to sidewalls), the widths of aperture W_i should be doubled and the centers of aperture S_i should be replaced by b_0 or a_{N+1} in (16) and (17). Preliminary computations are carried out for the special case of the shielded stripline to show the validity of the present method: a strip is placed symmetrically in homogeneous media. For the strip in the zero-thickness case (Fig. 4), the quasi-static line parameters can be calculated by using either the charge or the aperture field as source quantities. In addition, exact analytical solutions are available by conformal mapping for this case (Fig. 5). Fig. 4 shows the characteristic impedance

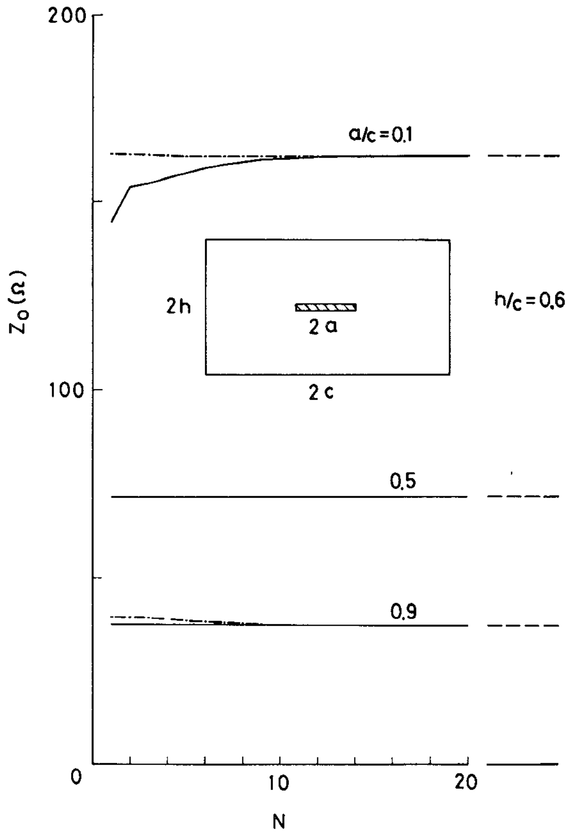

Fig. 4. Characteristic impedance of shielded strip of zero thickness for different numbers of basis functions: —·—·— upper bounds (charge); ——— lower bounds (aperture fields); ---- exact values (conformal mapping).

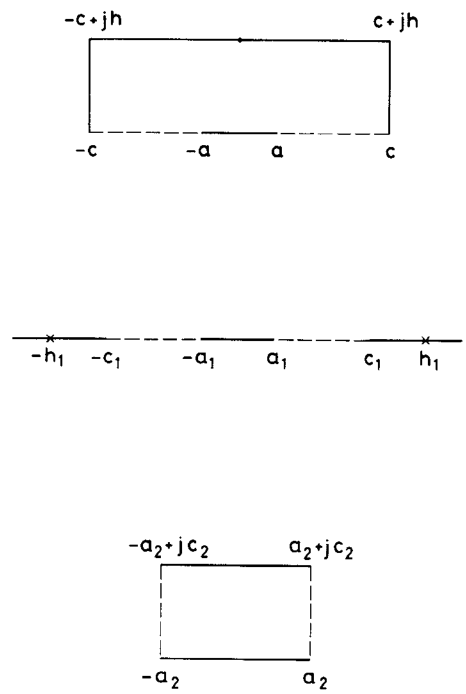

Fig. 5. A series of transformations for shielded strip: ——— electric wall, ---- magnetic wall.

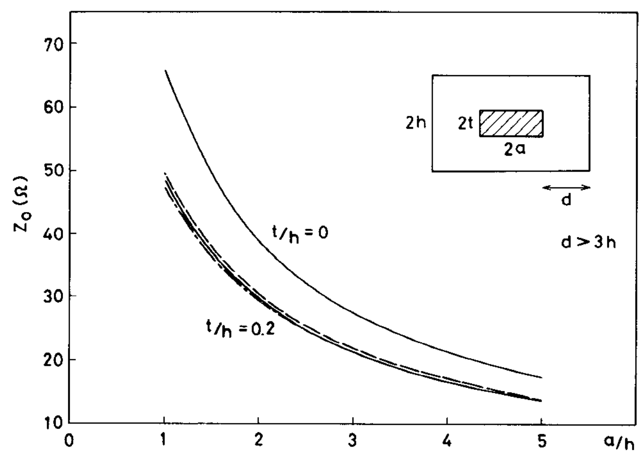

Fig. 6. Characteristic impedance of symmetrical shielded strip of finite thickness: ——— this theory; ---- upper bounds of [16]; —·—·— lower bounds of [16].

Z_0 as a function of the number N of basis functions. The value based on the charge places a lower bound on the line capacitance C and hence an upper bound on the characteristic impedance Z_0, whereas the value based on the aperture fields gives a lower bound to Z_0. The difference between the lower and upper bounds on Z_0, i.e., the margin of error, decreases with an increasing number of basis functions N, and the difference is less than 0.3 percent for N greater than 10, even for the worse case of $a/c = 0.1$. For thick-strip cases, the values based on the aperture fields are available, and their convergent tendency is similar to that for the zero-thickness case. However, exact analytical solutions cannot be obtained easily in general, nor can the value based on the charge distribution. However, for the special case, i.e., a single thick strip placed symmetrically in homogeneous media, the variational method is applicable and the upper and lower bounds on Z_0 can be obtained [16]. Fig. 6 compares the results obtained by the present method with those by [16] for this special case. The values of Z_0 by the present method, which gives a lower bound to Z_0, are larger than those of the lower bounds of [16] and lie between the upper and the lower bounds of [16].

Fig. 7 shows the frequency-dependent hybrid-mode values of the effective dielectric constants ϵ_{eff} of shielded microstrip for different numbers of basis functions N. For the thin-strip case ($t = 0$), numerical computations based on the current density [4] are included for comparison. We mention that hybrid-mode values based on both the current and the aperture field give neither lower nor upper bounds, but the difference between the values by the current and the aperture field decreases with N for the zero-thickness case, and reasonable convergence is observed for the thick-strip case. The numerical results of Figs. 4, 6, and 7 confirm that the computations based on the aperture field give sufficient accuracy to study the effect of the conductor thickness of wider and narrower strips for both the quasi-static and the frequency-dependent hybrid-mode calculations.

Fig. 8 shows the dispersion characteristics of the single microstrip with a uniaxially anisotropic substrate. The frequency-dependent hybrid-mode values converge to the

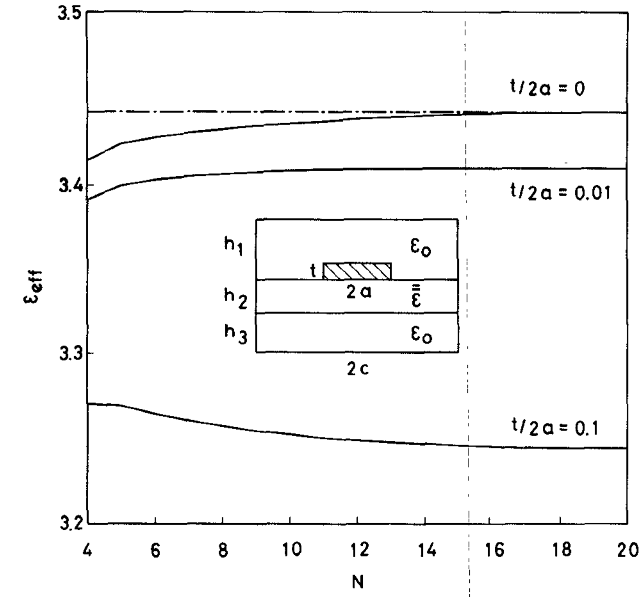

Fig. 7. Hybrid-mode values of effective dielectric constants of shielded strip: ——— aperture field basis, —·—·— current density basis. $\epsilon_{\parallel}=11.6$, $\epsilon_{\perp}=9.4$, $h_1=3$ (mm), $h_2=1$ (mm), $h_3=2$ (mm), $a=0.5$ (mm), $c=5$ (mm), $f=10$ (GHz).

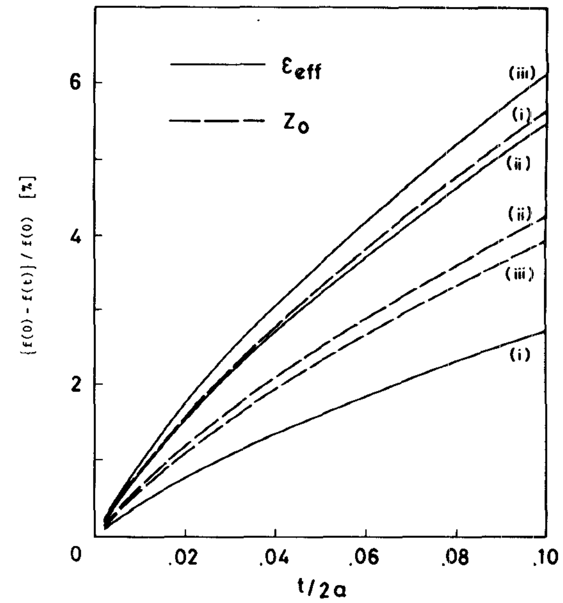

Fig. 9. Effect of metal coating thickness in shielded single stripline. $h_1=3$ (mm), $h_2=1$ (mm), $a=0.5$ (mm), $c=5$ (mm), (i) $\epsilon_{\parallel}=\epsilon_{\perp}=2.6$, (ii) $\epsilon_{\parallel}=11.6$, $\epsilon_{\perp}=9.4$, (iii) $\epsilon_{\parallel}=\epsilon_{\perp}=20$.

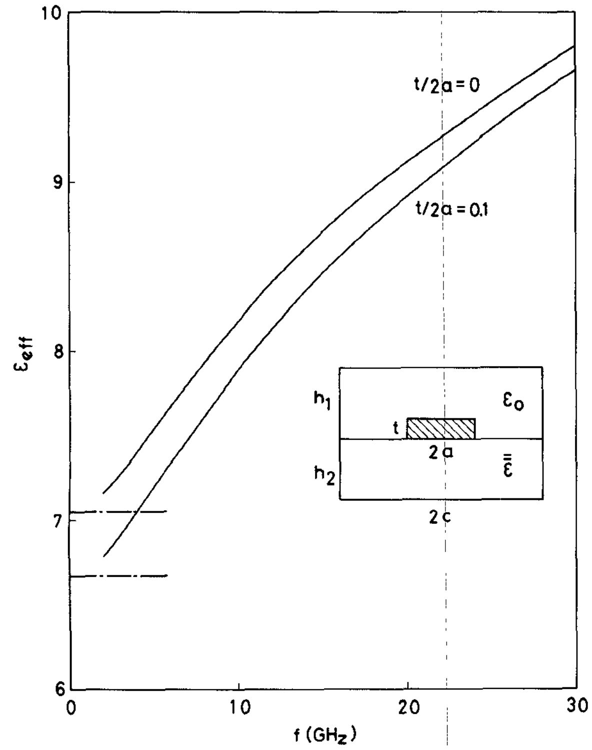

Fig. 8. Frequency-dependent characteristics of shielded stripline. $\epsilon_{\parallel}=11.6$, $\epsilon_{\perp}=9.4$, $h_1=3$ (mm), $h_2=1$ (mm), $a=0.5$ (mm), $c=5$ (mm).

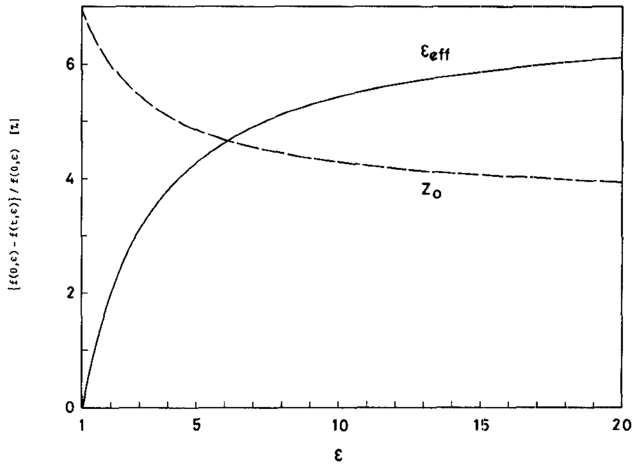

Fig. 10. Effect of metal coating thickness in shielded single stripline against dielectric constant of the substrate. $\epsilon_{\parallel}=\epsilon_{\perp}=\epsilon$, $h_1=3$ (mm), $h_2=1$ (mm), $t/2a=0.1$, $a=0.5$ (mm), $c=5$ (mm).

quasi-static values at the lower frequencies for both thin- and thick-strip cases. It should be noted that the dispersion curve for thick-strip cases is lower than that for the thin case ($t=0$) in the same way as the coplanar-type transmission lines [13], [14], but that in contrast to these transmission lines, the extent of lowering, i.e., the effect of the strip conductor thickness, becomes smaller at the higher frequencies. In the higher frequency range, the electromagnetic fields are concentrated near the line conductor edge in the coplanar-type transmission lines, which increases the effect of the strip conductor thickness. On the contrary, the electromagnetic fields are concentrated in the region of the substrate between the strip and the lower ground conductors in the higher frequency range, and the effect of the strip conductor thickness is decreased.

Fig. 9 shows the effect of the strip conductor thickness of the shielded strip with different substrates for the quasi-static case, and Fig. 10 shows the variation of the thickness effect with respect to the dielectric constant of the substrate for the quasi-static case. The influence of the metal coating thickness on the effective dielectric constant ϵ_{eff} increases with the dielectric constant of the substrate; however, the effect on the characteristic impedance Z_0 decreases with the dielectric constant (Figs. 9 and 10). This

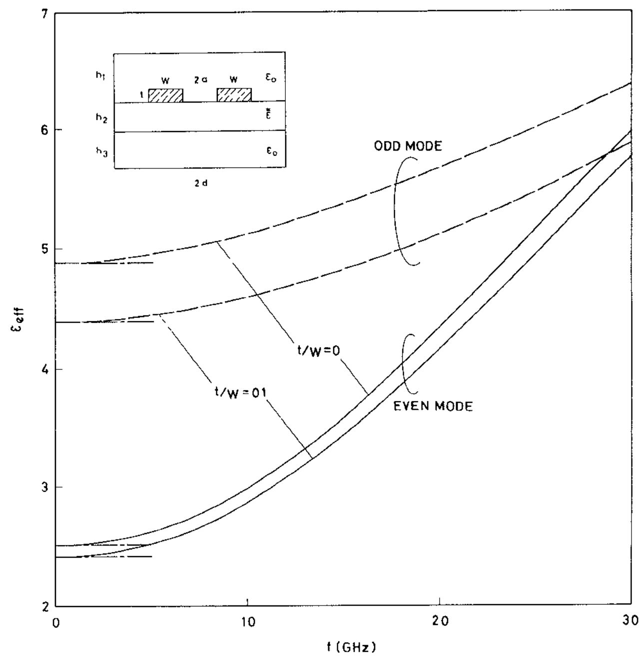

Fig. 11. Frequency-dependent characteristics of shielded coupled stripline. $\epsilon_{\parallel}=11.6$, $\epsilon_{\perp}=9.4$, $h_1=3$ (mm), $h_2=1$ (mm), $h_3=2$ (mm), $a=0.25$ (mm), $W=1$ (mm), $d=5$ (mm).

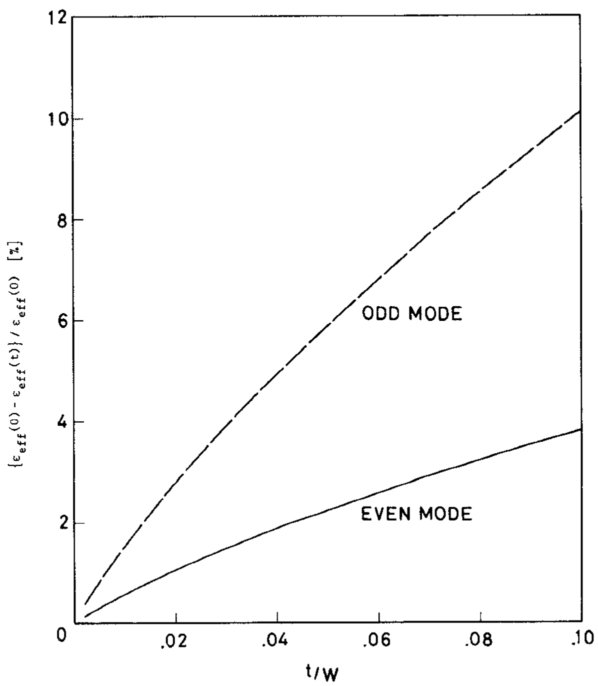

Fig. 12. Effect of metal coating thickness in shielded coupled stripline. $\epsilon_{\parallel}=11.6$, $\epsilon_{\perp}=9.4$, $h_1=3$ (mm), $h_2=1$ (mm), $h_3=2$ (mm), $a=0.25$ (mm), $W=1$ (mm), $d=5$ (mm).

can be explained by noting that the fractional change of the effective dielectric constant ϵ_{eff} of the single strip with finite metallization thickness may be approximated by

$$\{\epsilon_{\text{eff}}(t)-\epsilon_{\text{eff}}(0)\}/\epsilon_{\text{eff}}(0) \doteqdot \left(\frac{C+\Delta C}{C_0+\Delta C}-\frac{C}{C_0}\right)\cdot\left(\frac{C_0}{C}\right)$$
$$\doteqdot (\Delta C/C)-(\Delta C/C_0) \quad (18)$$

where C and C_0 are the capacitances of the zero-thickness cases with and without substrate, respectively; ΔC is the fractional line capacitance by the metallization thickness, whereas the fractional change of the characteristic impedance Z_0 may be approximated by $-(\Delta C/2C)-(\Delta C/2C_0)$ for the quasi-static case. Only the value of C, the capacitances for the case with substrate, will change according to the dielectric constant of the substrate.

Fig. 11 shows the dispersion characteristics of the coupled stripline with a uniaxially anisotropic substrate. Again, the frequency-dependent hybrid-mode values converge to the quasi-static values at the lower frequencies for all cases. It should be noted, however, that the difference in the effect of the strip conductor thickness between the even- and the odd-mode case is appreciable; i.e., the thickness effect of the odd-mode case is much larger than that of even-mode case. In the odd-mode case, the electromagnetic fields are concentrated near the aperture between the strip conductors, and they increase the effect of the strip conductor thickness. The effects of the strip conductor thickness of the even and the odd mode of the coupled strip are shown in Fig. 12.

IV. Conclusions

The effect of the metallization thickness in striplines is investigated on the basis of a unified approach, the quasi-static and frequency-dependent hybrid-mode formulations. Electric fields at the upper and lower aperture surfaces of the slot regions have been introduced as source quantities instead of the charge and current distributions on the strips for the zero-thickness approximation. Because of the use of the aperture fields, which cover wider regions, special care has been taken for accurate numerical calculations to obtain the appropriate evaluation of the effect of the metallization thickness, which consists of the portion of the propagation characteristics. Some numerical values reveal the metallization thickness effect of single and coupled striplines for both quasi-static and frequency-dependent cases. The evaluation of losses caused by finite conductivities of the conductors must take the metallization thickness into consideration because of the finite skin depth, and will be carried out by extending the present method.

References

[1] T. Itoh and R. Mittra, "Spectral-domain approach for calculating the dispersion characteristics of microstrip lines," *IEEE Trans. Microwave Theory Tech* , vol. MTT-21, pp 496–499, 1973.

[2] R. H. Jansen, "The spectral-domain approach for microwave integrated circuits," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, pp. 1043–1056, Oct. 1985.

[3] M. K. Krage and G. I. Haddad, "Frequency-dependent characteristics of microstrip transmission lines," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-20, pp. 678–688, Oct. 1972.

[4] Y. Fujkiki, T. Kitazawa, Y. Hayashi, and S. Suzuki, "Higher order modes in coplanar-type transmission lines," *Trans. IECE Japan*, vol. 58-B, no. 2, pp. 61–67, Feb. 1975.

[5] J. B. Knorr and A. Tufekcioglu, "Spectral-domain calculation of microstrip characteristic impedance," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 725–728, Sept. 1975.

[6] M. Horno, "Quasistatic characteristics of covered coupled microstrips on anisotropic substrates: Spectral and variational analy-

sis," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, pp. 1888–1892, Nov. 1982.

[7] T. Kitazawa and Y. Hayashi, "Propagation characteristics of striplines with multilayered anisotropic media," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-31, pp. 429–433, June 1983.

[8] B. J. Janiczak, "Accurate hybrid-mode approach for computing modes in three-line coupled microstrip structure in overlaid configuration," *Electron. Lett.*, vol. 20, pp. 825–826, Sept. 1984.

[9] T. Kitazawa and R. Mittra, "Analysis of asymmetric coupled striplines," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, pp. 643–646, July 1985.

[10] A. Nakatani and N. G. Alexopoulos, "Toward a generalized algorithm for the modeling of the dispersive properties of integrated circuit structures on anisotropic substrates," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, pp. 1436–1441, Dec. 1985.

[11] B. J. Janiczak, "Phase constant characteristics of generalized asymmetric three-coupled microstrip lines," *Proc. Inst. Elec. Eng.*, pt. H, vol. 132, pp. 23–26, Feb. 1985.

[12] T. Kitazawa and Y. Hayashi, "Asymmetrical three-line coupled striplines with anisotropic substrates," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-34, pp. 767–772, July 1986.

[13] T. Kitazawa, Y. Hayashi, and M. Suzuki, "Analysis of dispersion characteristics of slot line with thick metal coating," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp. 387–392, Apr. 1980.

[14] T. Kitazawa and R. Mittra, "Analysis of finline with finite metallization thickness," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-32, pp. 1484–1487, Nov. 1984.

[15] T. Kitazawa and Y. Hayashi, "Quasistatic characteristics of a coplanar waveguide with thick metal coating," *Proc. Inst. Elec. Eng.*, pt. H, vol. 133, no. 1, pp. 18–20, Feb. 1986.

[16]] R. E. Collin, *Field Theory of Guided Waves*. New York: McGraw-Hill, 1960, pp. 155–164.

Toshihide Kitazawa (M'84–SM'86) was born in Sapporo, Japan, on December 1, 1949. He received the B.E., M.E., and D.E. degrees in electronics engineering from Hokkaido University, Sapporo, Japan, in 1972, 1974, and 1977, respectively.

He was a Post-Doctoral Fellow of the Japan Society for the Promotion of Science from 1979 to 1980. Since 1980, he has been an Associate Professor of Electronic Engineering at the Kitami Institute of Technology, Kitami, Japan. From 1982 to 1984, he was a Visiting Assistant Professor of Electrical Engineering at the University of Illinois, Urbana.

Dr. Kitazawa is a member of the Information Processing Society of Japan and the Institute of Electronics, Information and Communication Engineers of Japan.