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DETERMINATION OF CAPACITANCE AND CONDUCTANCE MATRICES OF LOSSY SHIELDED COUPLED MICROSTRIP TRANSMISSION LINES

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Abstract—Laplace's equation is solved analytically for lossy shielded coupled microstrip transmission lines. The solution is represented in fourier series expression and is being used to determine the capacitance and conductance matrices of the structure. The method is examined using some examples and then some results are obtained.

1. INTRODUCTION

The multiconductor coupled microstrip transmission lines are used in RF, microwave and high-speed digital circuits extensively. To analyze these transmission lines one has to find the capacitance and conductance matrices of the structure [1]. The capacitance matrix of lossless structures is determined using conformal mapping transformations [2, 3], variational methods [4, 5], spectral domain techniques [6, 7], method of moments and green's function [8, 9], analytically for certain particular geometries [10] and solving Laplace's equation [11–13]. Some ones solve Laplace's equation numerically, e.g., finite difference method [11] and some others analytically, e.g., fourier series or fourier integral method [12, 13].

In this paper, both capacitance and conductance matrices of lossy structures are determined simply by solving Laplace's equation using fourier series method. The solutions are exact but they are expressed by means of infinite linear equations. Using these methods one can determine the voltage and current distribution on the strips, also. In Section 2, Laplace's equation is solved using fourier series method and the complete solution, i.e., after finding the unknown voltage coefficients, is used directly to determine the capacitance and conductance matrices of lossy structures. In Section 3, the solution of Laplace's equation is used to determine capacitance and conductance matrices of lossy structures without finding the unknown voltage coefficients. Finally, in Section 4 the capacitance and conductance matrices of some lossy and lossless structures are determined using the presented methods.

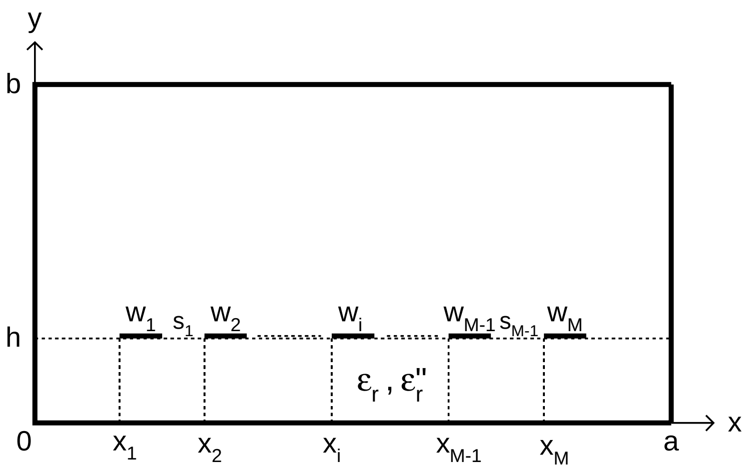

Figure 1. The cross section of a lossy shielded coupled microstrip transmission line.

Fig. 1 shows the cross section of the structure under analysis. There are M strips with arbitrary width of w_i, air gaps of s_i between them, located at x_i $(i = 1, 2, \dots, M)$. The dimension of the shield, a and b, the thickness of the substrate, h, and real and imaginary parts of dielectric constant of the substrate are shown in the figure.

2. THROUGH FINDING UNKNOWN COEFFICIENTS

In this section the capacitance, $\boldsymbol{C}$, and conductance, $\boldsymbol{G}$, matrices of the lossy structures are determined, after finding the unknown coefficients of the voltage distribution. For simplicity, it is assumed that the principal propagation mode of the lines is Quasi-TEM. This assumption is valid when the strip widths and their distances from the shield be small enough compared to the wavelength. Now, solving the two dimensional Laplace's equation with boundary conditions $V(x,0) = V(x,b) = V(0,y) = V(a,y) = 0$ and the continuity of voltage on the $y = h$, the voltage distribution is obtained as follows.

$$V(x,y) = \begin{cases} V_1(x,y) = \displaystyle\sum_{n=1}^{\infty} A_n \sin\left(\frac{n\pi}{a}x\right) \frac{\sinh\left(\frac{n\pi}{a}y\right)}{\sinh\left(\frac{n\pi}{a}h\right)}; & 0 \le y \le h \\ V_2(x,y) = \displaystyle\sum_{n=1}^{\infty} A_n \sin\left(\frac{n\pi}{a}x\right) \frac{\sinh\left(\frac{n\pi}{a}(b-y)\right)}{\sinh\left(\frac{n\pi}{a}(b-h)\right)}; & 0 \le y \le b \end{cases} \quad (1)$$

The normal component of the total current density (displacement plus viscosity) on the $y = h$ boundary is obtained using (1) as follows

$$J_z(x,h) = J_{z2}(x,h) - J_{z1}(x,h) = j\omega\varepsilon_0 \left[(\varepsilon_r - j\varepsilon_r'') \frac{\partial V_1}{\partial y}\bigg|_{y=h} - \frac{\partial V_2}{\partial y}\bigg|_{y=h} \right]$$
$$= \sum_{n=1}^{\infty} G_n A_n \sin\left(\frac{n\pi}{a}x\right) \quad (2)$$

in which

$$G_n = j\omega\varepsilon_0 \frac{n\pi}{a} \left[(\varepsilon_r - j\varepsilon_r'') \coth\left(\frac{n\pi}{a}h\right) + \coth\left(\frac{n\pi}{a}(b-h)\right) \right]$$
$$= \omega\varepsilon_0\varepsilon_r'' \frac{n\pi}{a} \coth\left(\frac{n\pi}{a}h\right) + j\omega\varepsilon_0 \frac{n\pi}{a} \left[\varepsilon_r \coth\left(\frac{n\pi}{a}h\right) + \coth\left(\frac{n\pi}{a}(b-h)\right) \right] \quad (3)$$

The real and imaginary parts of G_n are related to the displacement and viscosity current density, respectively. Now, if it is assumed a constant voltage V_0 on the i-th strip and zero voltage on the other strips, the boundary conditions for the voltage and total normal current density (the continuity condition) on the $y = h$ will become, respectively as follows

$$\sum_{n=1}^{\infty} A_n \sin\left(\frac{n\pi}{a}x\right) = \begin{cases} V_0; & \text{On the } i\text{-th strip} \\ 0; & \text{On the other strips} \\ V(x,h); & \text{Out of the strips} \end{cases} \tag{4}$$

$$\sum_{n=1}^{\infty} G_n A_n \sin\left(\frac{n\pi}{a}x\right) = \begin{cases} 0; & \text{Out of the strips} \\ J_z(x,h); & \text{On the strips} \end{cases} \tag{5}$$

The relations (4) and (5) are a system of dual series equations that must be solved. Using (4), one equation is found for A_n coefficients.

$$A_n = \frac{2}{a}\left[\int_{x_i}^{x_i+w_i} V_0 \sin\left(\frac{n\pi}{a}x\right) dx + \int_0^{x_1} V(x,h) \sin\left(\frac{n\pi}{a}x\right) dx \right.$$
$$\left. + \int_{x_M+w_M}^{a} V(x,h) \sin\left(\frac{n\pi}{a}x\right) dx + \sum_{k=1}^{M-1} \int_{x_k+w_k}^{x_{k+1}} V(x,h) \sin\left(\frac{n\pi}{a}x\right) dx \right] \tag{6}$$

Also, using (5) another equation is found for A_n coefficients.

$$A_n = \frac{2}{aG_n} \sum_{k=1}^{M} \int_{x_k}^{x_k+w_k} J_z(x,h) \sin\left(\frac{n\pi}{a}x\right) dx \tag{7}$$

Now, using (1) for $V(x,h)$ in (6) and using (2) for $J_z(x,h)$ in (7) and some mathematical operations, two infinite linear equations are found, respectively as follows

$$\sum_{m=1}^{\infty} \left\{ A_m \left[\cos\left(\frac{(m-n)\pi}{2}\right) \sin c\left(\frac{m-n}{2}\frac{W+S}{a}\right) \right.\right.$$
$$- \cos\left(\frac{(m+n)\pi}{2}\right) \sin c\left(\frac{m+n}{2}\frac{W+S}{a}\right)$$
$$- \sum_{k=1}^{M-1} \frac{s_k}{W+S} \left(\cos\left(\frac{(m-n)\pi}{a}\left(x_k + w_k + \frac{s_k}{2}\right)\right) \sin c\left(\frac{m-n}{2}\frac{s_k}{a}\right) \right.$$
$$\left.\left.\left. - \cos\left(\frac{(m+n)\pi}{a}\left(x_k + w_k + \frac{s_k}{2}\right)\right) \sin c\left(\frac{m+n}{2}\frac{s_k}{a}\right)\right)\right]\right\}$$
$$= 2V_0 \frac{w_i}{W+S} \sin\left(n\pi \frac{x_i + w_i/2}{a}\right) \sin c\left(\frac{n}{2}\frac{w_i}{a}\right) \tag{8}$$

$$A_n = \frac{1}{G_n}\sum_{m=1}^{\infty}\left\{A_m G_m \sum_{k=1}^{M}\frac{w_k}{a}\left[\cos\left(\frac{(m-n)\pi}{a}\left(x_k+\frac{w_k}{2}\right)\right)\right.\right.$$
$$\left.\left.\sin c\left(\frac{m-n}{2}\frac{w_k}{a}\right) - \cos\left(\frac{(m+n)\pi}{a}\left(x_k+\frac{w_k}{2}\right)\right)\sin c\left(\frac{m+n}{2}\frac{w_k}{a}\right)\right]\right\} \tag{9}$$

In (8), W and S are the total width of strips and the total gaps between the strips, respectively. Truncating n to N, two relations (8) and (9) become a linear equation system with $2N$ equations. Letting m and $n = 1, 2, 3, \dots, N$, two equations (8) and (9) can be written in a matrix form, respectively as follows

$$\boldsymbol{D}_{N\times N}\boldsymbol{A}_{N\times 1} = \boldsymbol{A}_{\boldsymbol{0}N\times 1} \tag{10}$$
$$\boldsymbol{H}_{N\times N}\boldsymbol{A}_{N\times 1} = \boldsymbol{A}_{N\times 1} \tag{11}$$

in which, $\boldsymbol{A} = [A_0, A_1, A_2, \dots, A_N]^T$ is the vector of unknown coefficients. Either of equations (10) or (11) has more than one solution, because they are related to only the strips or the gaps between them. But the combination of these two equations, which is followed, must have a unique solution.

$$\begin{bmatrix} \boldsymbol{D} \\ \boldsymbol{H}-\boldsymbol{1} \end{bmatrix}\boldsymbol{A} = \begin{bmatrix} \boldsymbol{A_0} \\ \boldsymbol{0} \end{bmatrix} \tag{12}$$

In (12), $\boldsymbol{1}$ is an $N \times N$ identity matrix. The matrix equation (12) can be solved by pseudo-inverse matrix method. Obviously, as the number of harmonics, i.e., N, increases, the accuracy of the solution is increased. According to the arguments of the sinc function in equations (8) and (9), N must be several times of $2a/\min(w_j)$. Meanwhile, since the vector $\boldsymbol{A_0}$ is real, the imaginary part of solution of (12), i.e., the imaginary part of unknown coefficients A_n, becomes very small. Also, regarding to (3) and (9), the unknown coefficients A_n, are obtained independent of the frequency ω.

After finding unknown coefficients A_n, one can now detemine the capacitance and conductance matrices of the lossy microstrip structure. The element $\boldsymbol{C}(j,i)$ is determined from integral of the surface charge density ρ_s on the j-th strip, in which the i-th strip is hold in V_0 voltage and the other strips are hold to zero voltage. Therefore, using (2)

$$\boldsymbol{C}(j,i) = \frac{1}{V_0}\int_{x_j}^{x_j+w_j}\rho_s(x,h)dx = \frac{1}{\omega V_0}\int_{x_j}^{x_j+w_j}\mathrm{Im}(J_z(x,h))dx$$
$$= \frac{w_j}{V_0\omega}\sum_{n=1}^{\infty}\left[\mathrm{Im}(G_nA_n)\sin\left(\frac{n\pi}{a}\left(x_j+\frac{w_j}{2}\right)\right)\sin c\left(n\frac{w_j}{2a}\right)\right] \tag{13}$$

Also, the element $\boldsymbol{G}(j,i)$ is determined from integral of total normal viscose current density on the j-th strip, in which the i-th strip is hold in V_0 voltage and the other strips are hold to zero voltage. Therefore, using (2)

$$\begin{aligned}\boldsymbol{G}(j,i) &= \frac{1}{V_0}\int\limits_{x_j}^{x_j+w_j} \mathrm{Re}(J_z(x,h))dx \\ &= \frac{w_j}{V_0}\sum_{n=1}^{\infty}\left[\mathrm{Re}(G_nA_n)\sin\left(\frac{n\pi}{a}\left(x_j+\frac{w_j}{2}\right)\right)\sin c\left(n\frac{w_j}{2a}\right)\right] \quad (14)\end{aligned}$$

3. WITHOUT FINDING UNKNOWN COEFFICIENTS

In this section the capacitance and conductance matrices of the lossy structures are determined without finding the unknown coefficients A_n. For this purpose we define a current function, using (2) as follows

$$I(x) \triangleq \int\limits_0^x J_z(x,h)dx = I_0 - \sum_{n=1}^{\infty} G_nA_n\frac{a}{n\pi}\cos\left(\frac{n\pi}{a}x\right) \quad (15)$$

in which

$$I_0 = \sum_{n=1}^{\infty} G_nA_n\frac{a}{n\pi} \quad (16)$$

The voltage and defined current function are constant on the strips and on the gaps between them, respectively. So, there will be two following boundary conditions.

$$\sum_{n=1}^{\infty} A_n\sin\left(\frac{n\pi}{a}x\right) = \begin{cases} V_i; & \text{On the } i\text{-th strip} \\ V(x,h); & \text{Out of the strips}\end{cases} \quad (17)$$

and

$$\sum_{n=1}^{\infty} G_nA_n\frac{a}{n\pi}\cos\left(\frac{n\pi}{a}x\right) = \begin{cases} I_0; & \text{for } 0\le x\le x_1 \\ I_0-\sum_{k=1}^{i} I_k; & \text{between } i\text{-th and } (i+1)\text{-th strip} \\ I_0 - I(x); & \text{on the strips} \\ I_0-\sum_{k=1}^{M} I_k; & \text{for } x_M+w_M\le x\le a\end{cases} \quad (18)$$

In (17) and (18), V_i and I_i are the voltage and total current of the i-th strip, respectively. Now, the system of dual series equations containing (17) and (18) must be solved. Using (17) and (18), two following equations are found for A_n coefficients.

$$A_n = \frac{2}{a}\left[\sum_{i=1}^{M}\int_{x_i}^{x_i+w_i} V_i \sin\left(\frac{n\pi}{a}x\right)dx + \int_0^{x_1} V(x,h)\sin\left(\frac{n\pi}{a}x\right)dx \right.$$
$$\left. + \int_{x_M+w_M}^{a} V(x,h)\sin\left(\frac{n\pi}{a}x\right)dx + \sum_{k=1}^{M-1}\int_{x_k+w_k}^{x_{k+1}} V(x,h)\sin\left(\frac{n\pi}{a}x\right)dx\right] \tag{19}$$

$$A_n = \frac{2}{aR_n}\frac{n\pi}{a}\left[\int_0^{a} I_0\cos\left(\frac{n\pi}{a}x\right)dx - \sum_{k=1}^{M-1}\int_{x_k+w_k}^{x_{k+1}}\sum_{i=1}^{k} I_i\cos\left(\frac{n\pi}{a}x\right)dx \right.$$
$$\left. - \sum_{k=1}^{M}\int_{x_k}^{x_k+w_k} I(x)\cos\left(\frac{n\pi}{a}x\right)dx - \int_{x_M+w_M}^{a}\sum_{i=1}^{M} I_i\cos\left(\frac{n\pi}{a}x\right)dx\right] \tag{20}$$

Now, using (1) for $V(x,h)$ in (24) and using (15) and (16) for $I(x)$ in (20) and by some mathematical operations, two infinite linear equations are found, respectively as follows

$$\sum_{m=1}^{\infty}\left\{A_m\left[\cos\left(\frac{(m-n)\pi}{2}\right)\sin c\left(\frac{m-n}{2}\frac{W+S}{a}\right)\right.\right.$$
$$-\cos\left(\frac{(m+n)\pi}{2}\right)\sin c\left(\frac{m+n}{2}\frac{W+S}{a}\right)$$
$$-\sum_{k=1}^{M-1}\frac{s_k}{W+S}\left(\cos\left(\frac{(m-n)\pi}{a}\left(x_k+w_k+\frac{s_k}{2}\right)\right)\sin c\left(\frac{m-n}{2}\frac{s_k}{a}\right)\right.$$
$$\left.\left.\left.-\cos\left(\frac{(m+n)\pi}{a}\left(x_k+w_k+\frac{s_k}{2}\right)\right)\sin c\left(\frac{m+n}{2}\frac{s_k}{a}\right)\right)\right]\right\}$$
$$=2\sum_{i=1}^{M}\frac{w_i}{W+S}\sin\left(n\pi\frac{x_i+w_i/2}{a}\right)\sin c\left(\frac{n}{2}\frac{w_i}{a}\right)V_i \tag{21}$$

$$\begin{aligned}A_n = &\frac{1}{G_n}\frac{n\pi}{a}\sum_{m=1}^{\infty}\left[A_m G_m \frac{a}{m\pi}\sum_{k=1}^{M}\frac{w_k}{a}\left(\cos\left((m+n)\pi\frac{2x_k+w_k}{2a}\right)\right.\right.\\ &\sin c\left((m+n)\frac{w_k}{2a}\right)+\cos\left((m-n)\pi\frac{2x_k+w_k}{2a}\right)\sin c\left((m-n)\frac{w_k}{2a}\right)\\ &\left.\left.-2\cos\left(n\pi\frac{2x_k+w_k}{2a}\right)\sin c\left(n\frac{w_k}{2a}\right)\right)\right]\\ &-\frac{2}{G_n}\frac{n\pi}{a}\sum_{k=1}^{M-1}\left(\frac{s_k}{a}\cos\left(n\pi\frac{x_k+w_k+x_{k+1}}{2a}\right)\sin c\left(n\frac{s_k}{2a}\right)\sum_{i=1}^{k}I_i\right)\\ &+\frac{2}{G_n}\frac{n\pi}{a}\frac{(x_M+w_M)}{a}\sin c\left(n\frac{x_M+w_M}{a}\right)\sum_{i=1}^{M}I_i \qquad (22)\end{aligned}$$

In (21), W and S are the total width of strips and the total gaps between the strips, respectively. Truncating n to N, two relations (21) and (22) become two N linear equations. Letting m and $n = 1, 2, 3, \ldots, N$, these two N linear equations can be written, respectively in matrix forms, as follows

$$\boldsymbol{D}_{N\times N}\boldsymbol{A}_{N\times 1} = \boldsymbol{E}_{N\times M}\boldsymbol{V}_{M\times 1} \qquad (23)$$

$$\boldsymbol{A}_{N\times 1} = \boldsymbol{F}_{N\times N}\boldsymbol{A}_{N\times 1} + \boldsymbol{G}_{N\times M}\boldsymbol{I}_{M\times 1} \qquad (24)$$

In (23) and (24), $\boldsymbol{A} = [A_0, A_1, A_2, \ldots, A_N]^T$, $\boldsymbol{V} = [V_0, V_1, V_2, \ldots, V_M]^T$ and $\boldsymbol{I} = [I_0, I_1, I_2, \ldots, I_M]^T$ are vectors representing the unknown coefficients A_n, the strip voltages and total currents of the strips, respectively. Eliminating the vector $\boldsymbol{A}$ between (23) and (24), and regarding to

$$\boldsymbol{I} = (\boldsymbol{G} + j\omega\boldsymbol{C})\boldsymbol{V} \qquad (25)$$

the capacitance and conductance matrices are determined, as follows

$$\boldsymbol{G} + j\omega\boldsymbol{C} = \left[\boldsymbol{E}^{-1}\boldsymbol{D}(\mathbf{1}-\boldsymbol{F})^{-1}\boldsymbol{G}\right]^{-1} \qquad (26)$$

in which $\mathbf{1}$ is an $N \times N$ identity matrix.

4. EXAMPLES AND RESULTS

In this section, first we investigate the validity of the proposed method using two examples about the lossless structures and then a comprehensive example for the lossy structures is presented.

As a first example, consider an $M = 8$ conductor lossless microstrip coupler with parameters $w_1 = \ldots = w_8 = 1$, $h =$

16, $s_1 = \ldots = s_7 = 1$, $a = 175$, $b = 116$ and $\varepsilon_r = 12.9$. The 20 different coefficients of the capacitance matrix (normalized to $\varepsilon_0 = 8.842 \times 10^{-12}$) obtained from the presented methods and from that proposed in [12] (reported in [13]) have been compared in Table 1.

Table 1.

	C_{11}	C_{22}	C_{33}	C_{44}	C_{12}	C_{23}	C_{34}	C_{45}	C_{13}	C_{24}
[12]	14.451	17.556	17.705	17.731	-6.610	-5.940	-5.875	-5.865	-1.473	-1.182
Proposed	14.267	17.259	17.407	17.432	-6.454	-5.796	-5.732	-5.722	-1.462	-1.177
	C_{35}	C_{14}	C_{25}	C_{36}	C_{15}	C_{26}	C_{16}	C_{27}	C_{17}	C_{18}
[12]	-1.150	-0.647	-0.492	-0.477	-0.351	-0.261	-0.214	-0.163	-0.145	-0.137
Proposed	-1.145	-0.643	-0.491	-0.475	-0.349	-0.261	-0.212	-0.162	-0.143	-0.134

For a second example consider an $M = 2$ conductor lossless microstrip coupler with parameters $w_1 = w_2 = w$, $h = 1$, $s = 1$, a and b very large (e.g., $a = b = 30h$) and $\varepsilon_r = 2.35$. The even and odd mode characteristic impedances of this coupler obtained from the presented methods and by that proposed in [3] (reported in [13]) have been compared in Table 2.

Table 2.

	Proposed Method		Wan Method [3]	
w/h	Z_{even}	Z_{odd}	Z_{even}	Z_{odd}
0.10	229.2	170.2	228.8	168.2
0.25	182.7	132.3	182.4	130.0
0.50	145.9	105.7	145.3	103.0
0.75	122.7	89.5	123.2	88.1
1.00	107.3	79.4	107.6	78.0
1.25	95.6	71.8	95.9	70.4
1.75	79.0	60.7	79.0	59.4
2.25	67.4	53.0	67.3	52.0

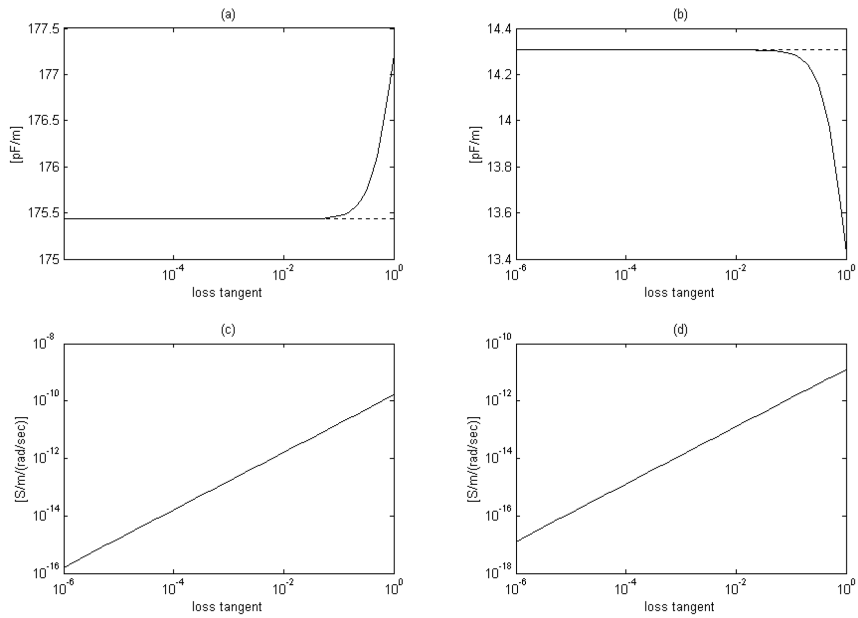

Figure 2. The elements of capacitance and conductance matrices of a lossy shielded coupled microstrip transmission line versus the loss tangent (a) C_{11} (b) $-C_{12}$ (c) G_{11}/ω (d) $-G_{12}/\omega$.

As it is clear from these two examples, the results of the presented method have a little discrepancy compared to [3] and [12]. Therefore one may satisfy about the accuracy of the presented methods.

Now, as a third example consider an $M = 2$ conductor lossy microstrip coupler with parameters $w_1 = w_2 = 1$, $h = 1$, $s = 1$, $a = b = 20$ and $\varepsilon_r = 10$. Fig. 2 shows the values of C_{11}, C_{12}, G_{11}/ω and G_{12}/ω versus the loss tangent of substrate, $\tan(\delta) = \varepsilon_r''/\varepsilon_r$.

From Fig. 2 and the obtained relations, the following results are obtained.

1. The self capacitances $\boldsymbol{C}(i,i)$ will be increased and the coupling capacitances $\boldsymbol{C}(j,i)$ will be decreased, if the loss tangent is increased severely. This is because as the loss tangent is increased, the electric field is concentrated under the strips more and more.
2. The capacitance matrix is independent from frequency and the conductance matrix is proportional to frequency. So, the conductance matrix will become important in the high frequencies.
3. The capacitance matrix of the lossy structures will be equal to

the capacitance matrix of the lossless structure, only if the loss tangent is being very small, e.g., smaller than 0.01.

5. CONCLUSION

Two methods are given for determination the capacitance and conductance matrices of a lossy shielded coupled microstrip transmission lines. Fourier series solution of Laplace's equation is used and the exact solutions are expressed in terms of infinite but simple evaluated linear equations. The losses of substrate change the values of elements of the capacitance matrix a little.

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