The Incremental Inductance Rule in Quasi-TEM Coupled Transmission Lines

Gian Guido Gentili and Andrea Melloni

Abstract—**The application of the incremental inductance rule is described for the computation of losses in quasi-TEM coupled transmission lines. It is shown that the well-known formula valid for the single-line case can be extended to the case of normal modes travelling in general coupled structures providing one uses the power-current modal characteristic impedance definition [1]. Numerical results are shown for several coupled lines systems.**

I. Introduction

THE INCREMENTAL inductance rule (also known as Wheeler's rule [2]) is very popular for the analysis of lossy transmission lines both TEM and quasi-TEM. Quite often, losses in such structures are predominantly due to finite conductivity of metalizations and the contribution of imperfect dielectrics is usually at least one order of magnitude smaller than the former [3]. Although the analysis of single lossy quasi-TEM lines has been widely investigated by Wheeler's rule (see e.g. [4]–[6]), in the literature the problem of lossy coupled quasi-TEM lines has not been dealt with, except for the case of two symmetrical lines (see e.g. [7]), where Wheeler's rule applies with no modification with respect to the single line case.

On the other hand, the analysis of arbitrary systems of quasi-TEM coupled lines is important both for the realization of classical microwave devices (filters and directional couplers) and of high-speed links [8]–[10], and there is a considerable interest in models that can deal with the lossy case. Lossy quasi-TEM coupled lines have been analyzed either by full-wave methods or by the concept of surface resistance (e.g. [3], [11]–[13]). By the latter approach, losses can be computed e.g. by integrating the square of the current density (computed for the lossless case) over the cross-section of all conductors [3], [11], [14]. The effectiveness of such analysis depends on many factors. Apart from metal conductivity and frequency of operation, the shape of the conductors is also a significant parameter. For instance, a zero-thickness stripline exhibit infinite attenuation due to the non-integrable singularity of the square of current density. One should thus compute the current density of the lossless case by solving the boundary value problem for the finite metal thickness case. Some modifications to this approach include the possibilty to take into account metals fully penetrated by currents and has been used for high-speed digital links [15].

An alternative approach to the concept of surface resistance is the use of Wheeler's incremental inductance rule [2]. The extension of such rule to the general case of N quasi-TEM coupled lines requires the introduction of a modal characteristic impedance. Unlike the case of two symmetrical coupled lines, in the general N-line case the modal characteristic impedance was observed to have *different values* according to the *definition* one adopts to compute it [1]. Thus, in the general N-line case, the extension of Wheeler's rule requires to resort to its basic energetical meaning. It is shown in the following sections that the modal attenuation constant is defined by a quite analogous formula as that holding for the single-line case, providing one uses the power-current (PI) definition of modal characteristic impedance.

II. Statement of the Problem

Consider a system of N lossless coupled transmission lines in a inhomogeneous medium as shown in Fig. 1. Under the quasi-TEM assumption, the structure can be fully characterized by a $N \times N$ capacitance matrix per unit length (p.u.l.) $\boldsymbol{C}$ and a $N \times N$ inductance matrix p.u.l. $\boldsymbol{L}$ [16]. Time-harmonic propagation of the current and voltage waves along the system of coupled transmission lines is described by the well known generalized Kirchoff's equations

$$\frac{1}{c}\boldsymbol{v} = \boldsymbol{L}\boldsymbol{i} \tag{1}$$

$$\frac{1}{c}\boldsymbol{i} = \boldsymbol{C}\boldsymbol{v} \tag{2}$$

where, c is the speed of propagation (unknown) and $\boldsymbol{v}$ and $\boldsymbol{i}$ are column vectors containing the voltages and currents travelling on the lines. Time dependence $e^{j\omega t}$ is assumed and suppressed.

Substitutions of (1) into (2) and vice-versa lead to the following eigenvalue equations for the current waves:

$$\lambda_k^2 \boldsymbol{i}_k = \boldsymbol{C}\boldsymbol{L}\boldsymbol{i}_k \tag{3}$$

while for the voltage waves

$$\lambda_k^2 \boldsymbol{v}_k = \boldsymbol{L}\boldsymbol{C}\boldsymbol{v}_k. \tag{4}$$

In (3) and (4), k identifies the mode, $\boldsymbol{i}_k$ and $\boldsymbol{v}_k$ are current and voltage eigenvectors and λ_k, the square root of the eigenvalue in (3) and (4), is the inverse of the speed of propagation. Now let's organize parameters λ_k in a diagonal matrix $\boldsymbol{\Lambda}$ and vectors

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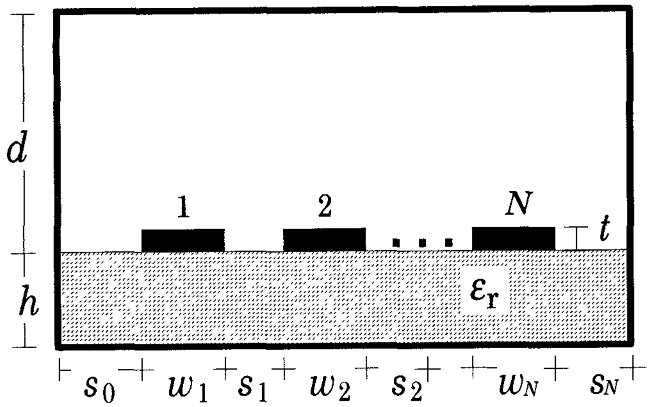

Fig. 1. Reference geometrical parameters for N coupled microstrips.

$\boldsymbol{i}_k$ and $\boldsymbol{v}_k$, normalized according to

$$\boldsymbol{i}_k^{\mathrm{T}}\boldsymbol{i}_k = 1, \quad k = 1 \cdots N \tag{5}$$
$$\boldsymbol{v}_k^{\mathrm{T}}\boldsymbol{v}_k = 1, \quad k = 1 \cdots N \tag{6}$$

as columns of matrices $\boldsymbol{M}_i$ and $\boldsymbol{M}_v$, respectively (the suffix 'T' indicates transposition).

As shown in [1], each mode that propagates along the coupled lines system can be associated with a characteristic impedance. According to the various possible definitions of characteristic impedance (PI, power-current, PV, power-voltage and VI, voltage-current), one finds that the *normalization independent* diagonal matrix $\boldsymbol{Z}_d$ of modal characteristic impedances can be expressed as follows [1]:

$$\boldsymbol{Z}_d^{(\mathrm{PI})} = \boldsymbol{\Lambda}^{-1}\boldsymbol{M}_i^{\mathrm{T}}\boldsymbol{L}\boldsymbol{M}_i \tag{7}$$
$$\boldsymbol{Z}_d^{(\mathrm{PV})} = (\boldsymbol{\Lambda}^{-1}\boldsymbol{M}_v^{\mathrm{T}}\boldsymbol{C}\boldsymbol{M}_v)^{-1} \tag{8}$$
$$\boldsymbol{Z}_d^{(\mathrm{VI})} = (\boldsymbol{Z}_d^{(\mathrm{PI})}\boldsymbol{Z}_d^{(\mathrm{PV})})^{1/2}. \tag{9}$$

Correspondingly one can define modal inductance and capacitance p.u.l. as

$$\boldsymbol{L}_d^{(\mathrm{PI})} = \boldsymbol{M}_i^{\mathrm{T}}\boldsymbol{L}\boldsymbol{M}_i \tag{10}$$
$$\boldsymbol{L}_d^{(\mathrm{PV})} = \boldsymbol{\Lambda}^2(\boldsymbol{M}_v^{\mathrm{T}}\boldsymbol{C}\boldsymbol{M}_v)^{-1} \tag{11}$$
$$\boldsymbol{L}_d^{(\mathrm{VI})} = \boldsymbol{M}_v^{-1}\boldsymbol{L}\boldsymbol{M}_i \tag{12}$$
$$\boldsymbol{C}_d^{(\mathrm{PI})} = \boldsymbol{\Lambda}^2(\boldsymbol{M}_i^{\mathrm{T}}\boldsymbol{L}\boldsymbol{M}_i)^{-1} \tag{13}$$
$$\boldsymbol{C}_d^{(\mathrm{PV})} = \boldsymbol{M}_v^{\mathrm{T}}\boldsymbol{C}\boldsymbol{M}_v \tag{14}$$
$$\boldsymbol{C}_d^{(\mathrm{VI})} = \boldsymbol{M}_i^{-1}\boldsymbol{C}\boldsymbol{M}_v. \tag{15}$$

As shown in [1], according to the different definitions one adopts for the (PI, PV, VI), in the general case one finds *different values* for the modal characteristic impedance. The three diagonal matrices coincide in value when matrices $\boldsymbol{L}$ and $\boldsymbol{C}$ commute ($\boldsymbol{LC} = \boldsymbol{CL}$ [1]). This latter condition holds e.g. in case of two quasi-TEM symmetrical coupled lines (see also the special case pointed out in [17]).

III. The Lossy Case

Throughout this paper losses are assumed to be due to finite conductivity of metalization only. The perturbational model used in this work for lossy quasi-TEM coupled transmission lines assumes, quite analogously as in the single-line case, that propagation for each mode can be described according to a complex propagation constant

$$\gamma_k = \alpha_k + j\beta_k \tag{16}$$

in which the imaginary part is the lossless propagation constant, and the real part is the attenuation constant. The fields are supposed to be the same as in the lossless case [2]. In the multi-line case, this means that the voltage and current eigenvector matrices are supposed to be the same as in the lossless case.

As shown by Wheeler [2], for good conductors the magnetic energy ΔW p.u.l. stored in the skin depth region times twice the angular frequency equals the power P_d p.u.l. dissipated due to the finite conductivity. In other words

$$2\omega\Delta W = P_d. \tag{17}$$

The magnetic energy in the skin-depth region is then computed as

$$\Delta W = \frac{\delta}{2}\frac{\partial W}{\partial n} \tag{18}$$

where $\delta = \sqrt{2/(\omega\mu\sigma)}$ is the skin depth, σ is the metal conductivity and n is the normal to the conductor surface pointing inward.

Now let the excitation in the coupled lines be represented by the generic kth current eigenvector. The associated magnetic energy is $W_k = (1/4)\boldsymbol{i}_k^T\boldsymbol{L}\boldsymbol{i}_k$. Let then the increments in magnetic energy due to each mode be organized in a diagonal matrix $\Delta\boldsymbol{W}$. By recalling that in the definition of the incremental inductance rule the fields are assumed to be the same as in the lossless case, matrix $\Delta\boldsymbol{W}$ takes on the form

$$\Delta\boldsymbol{W} = \frac{\delta}{8}\frac{\partial}{\partial n}[\boldsymbol{M}_i^{\mathrm{T}}\boldsymbol{L}\boldsymbol{M}_i] = \frac{\delta}{8}\boldsymbol{M}_i^{\mathrm{T}}\frac{\partial \boldsymbol{L}}{\partial n}\boldsymbol{M}_i = \frac{\delta}{8}\frac{\partial \boldsymbol{L}_d^{(\mathrm{PI})}}{\partial n} \tag{19}$$

by comparison with (10), having defined

$$\frac{\partial \boldsymbol{L}_d^{(\mathrm{PI})}}{\partial n} = \boldsymbol{M}_i^{\mathrm{T}}\frac{\partial \boldsymbol{L}}{\partial n}\boldsymbol{M}_i. \tag{20}$$

Then the powers dissipated according to each mode, organized in a diagonal matrix $\boldsymbol{P}_d$, because of (18) can be expressed as

$$\boldsymbol{P}_d = \frac{\omega\delta}{4}\frac{\partial \boldsymbol{L}_d^{(\mathrm{PI})}}{\partial n} \tag{21}$$

while the travelling power $\boldsymbol{P}_f$ associated to each mode is given by $\boldsymbol{P}_f = (1/2)\boldsymbol{\Lambda}^{-1}\boldsymbol{M}_i^{\mathrm{T}}\boldsymbol{L}\boldsymbol{M}_i = (1/2)\boldsymbol{Z}_d^{(\mathrm{PI})}$.

Thus, from the definition of the attenuation constant, the diagonal matrix $\boldsymbol{\alpha}_d$ of modal attenuation constants is given by

$$\boldsymbol{\alpha}_d = \frac{1}{2}\boldsymbol{P}_d\boldsymbol{P}_f^{-1} = \frac{\omega\delta}{4}\boldsymbol{Y}_d^{(\mathrm{PI})}\frac{\partial \boldsymbol{L}_d^{(\mathrm{PI})}}{\partial n} = \frac{R_s}{2\mu}\boldsymbol{Y}_d^{(\mathrm{PI})}\frac{\partial \boldsymbol{L}_d^{(\mathrm{PI})}}{\partial n} \tag{22}$$

where we have set $\boldsymbol{Y}_d^{(\mathrm{PI})} = (\boldsymbol{Z}_d^{(\mathrm{PI})})^{-1}$ and where $R_s = \sqrt{\omega\mu/(2\sigma)}$ is the surface resistivity of the metal. (22) is the formulation of Wheeler's incremental inductance rule for a system of coupled quasi-TEM transmission lines. Note that in the definition of the incremental magnetic energy, matrix

TABLE I
EVEN AND ODD-MODE ATTENUATION CONSTANT (dB/m) FOR TWO SYMMETRICAL MICROSTRIPS ANALYZED IN [7]. ASTERISKS REFER TO RESULTS OBTAINED IN THIS WORK

			α_{even}		α_{odd}	
ε_r	w/h	s/h	[7]	*	[7]	*
10.4	0.785	0.304	3.2	3.2	7.2	8.0
9.5	0.87	0.212	2.8	2.9	8.8	9.0
9.5	0.87	0.162	2.8	2.9	10.1	10.4

TABLE II
EVEN AND ODD-MODE ATTENUATION CONSTANT (dB/m) CONVERGENCE PATTERN FOR THE FIRST LINE IN TABLE I

		$\Delta n/t = 0.1$		$\Delta n/t = 0.01$		$\Delta n/t = 0.001$	
N_w	N_t	α_{even}	α_{odd}	α_{even}	α_{odd}	α_{even}	α_{odd}
10	3	3.24	8.10	3.21	8.03	3.21	8.02
20	6	3.20	8.01	3.21	8.02	3.21	8.02

$\boldsymbol{M}_i^{\mathrm{T}}(\partial \boldsymbol{L}/\partial n)\boldsymbol{M}_i$ is not exactly diagonal, but only the diagonal elements are retained, because the incremental magnetic energy, according to the model represented by (16), is computed for each mode separately. From (22) one can observe that by the power-current definition of modal characteristic impedance one gets a formula for the modal attenuation constant which is quite analogous to that obtained in the single-line case [4]. Equation (22) also points out that although the normalization used for the current eigenvector matrix is arbitrary (since it simplifies out in (22)), the *definition* of modal characteristic impedance is not.

IV. DISCUSSION AND NUMERICAL RESULTS

In order to test the analytical procedure and to present some reference data, several numerical results on the modal attenuation in systems of quasi-TEM coupled lines have been produced.

The results have been generated by a numerical method to compute the inductance and capacitance matrices in coupled quasi-TEM lines with finite metalization thickness. The method uses an efficient Green's function representation for shielded multilayered dielectric media, by which accurate results can be obtained [18]. The surface charge distribution of Poisson's equation is discretized into a picewise linear function with an efficient non-uniform discretization scheme. Galerkin's method is then applied to convert the functional equation to a matrix one, which is solved by standard Gaussian elimination. As a whole, the method yields a good representation of charge density and an accurate evaluation of matrix $\boldsymbol{C}$ and $\boldsymbol{L}$ (actually $\boldsymbol{L} = \boldsymbol{C}_0^{-1}\mu_0\epsilon_0, \boldsymbol{C}_0$ being the capacitance matrix when all dielectrics are replaced by air).

At first some results for two symmetrical coupled microstrip lines are shown (Table I). The results obtained are compared with [7], and only the strip's contribution to attenuation has been considered for both [7] and the results obtained in this work. A reasonable agreement can be observed between the two sets of data. The results obtained in this work refer to two shielded coupled microstrip lines, but the shielding was taken far enough to have no influence on the results reported. The normal derivative of the inductance matrix was computed by a finite-difference approximation. Thus we have set $\partial \boldsymbol{L}/\partial n \simeq \Delta \boldsymbol{L}/\Delta n$. The value Δn was chosen as $t/20$ and a satisfactory approximation of the normal derivative was obtained.

For comparison, the convergence pattern of the even and odd-mode attenuation in the first line of Table I (which, for the odd-mode, is somewhat higher than in [7]) is shown in Table II. The table shows the results obtained by varying the number N_w of basis functions along the strip widths, the number N_t of basis functions along the strip thickness and parameter $\Delta n/t$ (see [18]). As shown in the table, the convergence to the values reported in Table I is very good. Comparison results have been obtained also for the single-line case and a very good agreement has been obtained with both [6] and [5]. They are not shown in this paper for brevity.

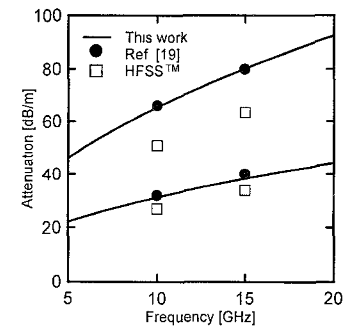

Fig. 2. Symmetrical microstrips analyzed in [19]. Referring to Fig. 1, $N = 2$, $s_0 = s_2 = 0.515$ mm, $w_1 = w_2 = 0.07$ mm, $s_1 = 0.03$ mm, $t = 3$ μm, $h = 0.1$ mm, $d = 2$ mm, $\sigma = 4.1 \cdot 10^7$ S/m, $\epsilon_r = 12.9$.

A further comparison is shown in Fig. 2. The figure refers to the two symmetrical shielded microstrips analyzed in [19] using the incremental inductance rule. Results from [19] were read from the plotted curve and are therefore affected by small errors. In spite of that a very good agreement with the results obtained in this paper can be observed for both the even and the odd mode. In the figure results from program HFSS™ are reported too [20]. The program uses the finite element method to analyze the structure and, as shown in the figure, some discrepancies are observed especially for the odd mode. In the frequency range shown in Fig. 2 dispersion can be neglected for the odd mode [19].

A further comparison is shown in Fig. 3 and it refers to a system of four coupled microstrips. Modes in the figure are labelled according to the number of sign changes in the associated voltage eigenvector [15]. Also in this case, program HFSS™ predicts a lower attenuation constant with respect to the values obtained in this work. However a reasonable agreement is observed between the two sets of data.

In all the following figures, the normalized parameter

$$A = 8.686\alpha \frac{h}{R_s\sqrt{\epsilon_{r,\mathrm{eff}}}} \tag{23}$$

which is mode-dependent and represents a modal normalized attenuation expressed in dB, is shown.

In Fig. 4 some results are presented for two asymmetrical coupled lines (see Fig. 1 for the definitions of the geometrical

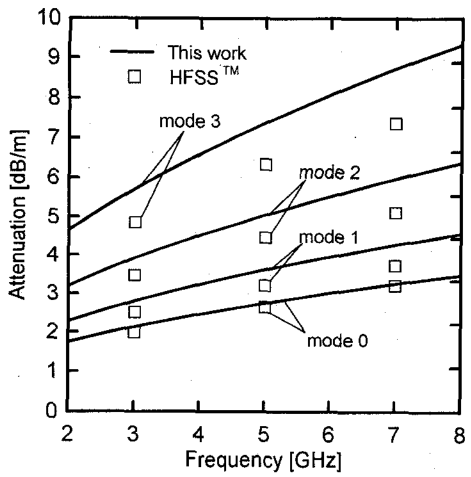

Fig. 3. A system of four microstrips. Referring to Fig. 1, $N = 4$, $s_0 = s_4 = 3$ mm, $w_1 = w_4 = 0.6$ mm, $w_2 = w_3 = 0.3$ mm, $s_1 = s_3 = 0.3$ mm, $s_2 = 0.2$ mm, $t = 10\ \mu$m, $h = 0.635$ mm, $d = 6$ mm, $\sigma = 5.1 \cdot 10^7$ S/m, $\epsilon_r = 9.8$.

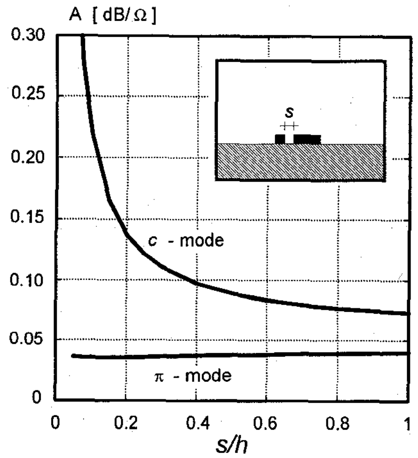

Fig. 4. Parameter A for a system of two non-symmetrical microstrips. Referring to Fig. 1, $N = 2$, $s_0/h = s_2/h = 5$, $w_1/h = 0.1$, $w_2/h = 0.5$, $d/h = 5$, $t/h = 0.1$, $\epsilon_r = 9.8$.

parameters). In this case the lines are characterized by a π-mode (voltages having the same sign) and a c-mode (voltages of opposite sign). The behavior of the attenuation constants is quite similar to the case of two symmetrical lines.

Some results for three-line systems are shown in Figs. 5–7. In Fig. 5 a symmetrical three-line system with three narrow strips ($w_i/h = 0.2$) has been analyzed. In the figure the signs of the current eigenvectors for each mode are shown. A '0' indicates that as a whole no *average* current flows in the strip. The two modes '$+-+$' and '$+0-$' have approximately the same value of parameter A for a rather wide range of s/h values, while mode '$+++$' has the lowest value of parameter A.

A similar structure is analyzed in Fig. 6. In this case the center strip was made wider ($w_2/h = 0.5$) and the outer strips somewhat narrower ($w_1/h = w_3/h = 0.1$). In spite of that, the normalized attenuation of mode '$+-+$' has not appreciably changed with respect to the previous case, while that of mode '$+0-$' has significantly changed.

A completely asymmetrical structure has been analyzed in Fig. 7. Also in this case the mode having the greatest number of sign changes in the eigenvector exhibits the largest normalized attenuation and the mode having no sign changes has the lower normalized attenuation A.

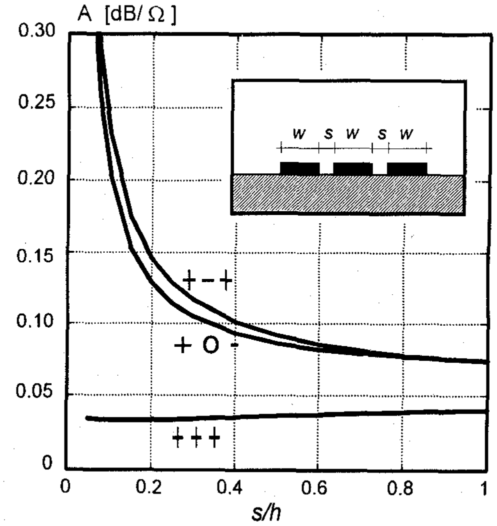

Fig. 5. Parameter A for a system of three microstrips. Referring to Fig. 1, $N = 3$, $s_0/h = s_3/h = 5$, $w_1/h = w_2/h = w_3/h = 0.2$, $d/h = 5$, $t/h = 0.1$, $\epsilon_r = 9.8$.

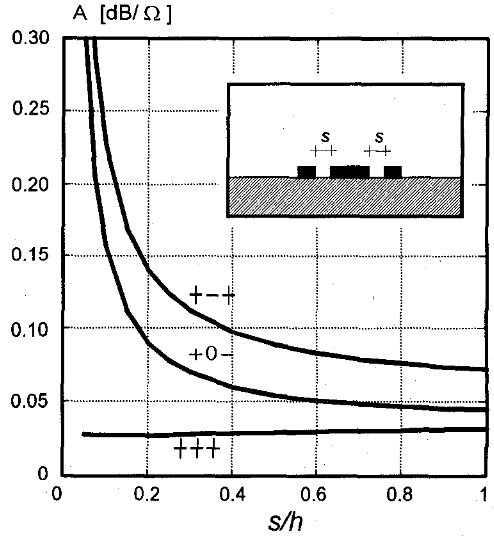

Fig. 6. Parameter A for a system of three microstrips. Referring to Fig. 1, $N = 3$, $s_0/h = s_3/h = 5$, $w_1/h = w_3/h = 0.1$, $w_2/h = 0.5$, $d/h = 5$, $t/h = 0.1$, $\epsilon_r = 9.8$.

V. Conclusion

Some results on the application of the incremental inductance rule have been presented for systems of quasi-TEM coupled transmission lines.

It is shown that, although in a system of coupled quasi-TEM lines modal characteristic impedance takes on different values according to the definition one applies (power-current, power-voltage, voltage-current), the one which is directly related to losses is the power-current one.

The analysis of several coupled lines systems was then presented graphically in normalized form to provide reference data for some asymmetrical multiconductor structures.

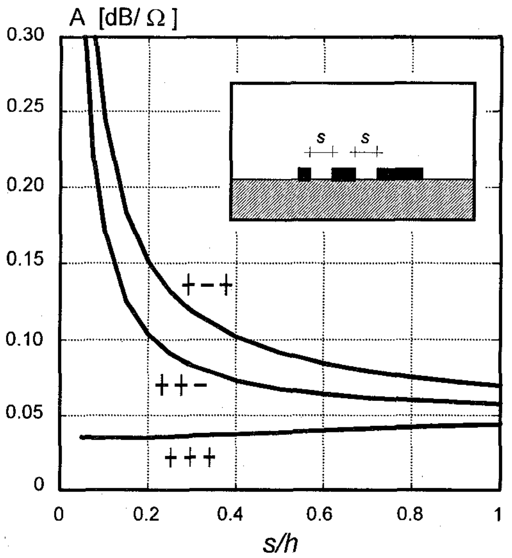

Fig. 7. Parameter A for a system of three microstrips. Referring to Fig. 1, $N = 3$, $s_0/h = s_3/h = 5$, $w_1/h = 0.1$, $w_2/h = 0.5$, $w_3/h = 1$, $d/h = 5$, $t/h = 0.1$, $\epsilon_r = 9.8$.

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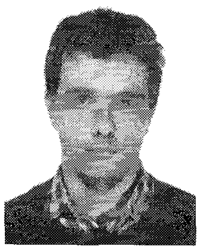

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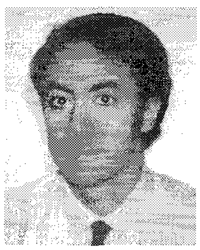

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