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Research Article

Solving the Complexity Problem in the Electronics Production Process by Reducing the Sensitivity of Transmission Line Characteristics to Their Parameter Variations

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In this paper we consider the complexity problem in electronics production process. Particularly, we investigate the ways to reduce sensitivity of transmission line characteristics to their parameter variations. The reduction is shown for the per-unit-length delay and characteristic impedance of several modifications of microstrip transmission lines. It can be obtained by means of making an optimal choice of parameter values, enabling proper electric field redistribution in the air and the substrate. To achieve this aim we used an effective simulation technique and software tools. Taken together, for the first time, they have allowed formulating general approach which is relevant to solve a wide range of similar tasks.

1. Introduction

Electronics is more and more widely used in human life. Complexity of electronics is continuously increasing. It results in increasing the number of electronics parameters. Unfortunately, the parameters undergo undesirable variations caused by the manufacturing process. As undesirable results, we obtain the reduced yield ratio in mass production and the reduced quality of a product or the increased production cycle due to necessity of a product to be redesigned or reproduced.

To treat the problem we can consider two main parts of the problem: concerning electronic components and supporting structures for their packaging. As for components, their nomenclature is very wide. Nevertheless, a great attention is paid to ensure their tolerance. As for supporting structures, their number is very small (a printed circuit board (PCB), an integrated circuit (IC), and a chip). The most popular structure is a PCB, while an IC and a chip can be considered as dedicated to electronic components, especially due to the recent trends of system-in-package (SiP) and system-on-chip (SoC) designs. Thus, a PCB is becoming the main concern of a designer, while a microstrip-like-lines are the main paths for signal propagation in PCBs and even ICs and chips as well. Therefore, to assure stable characteristics of the lines are an important task, the importance is illustrated by a representative example in Figure 1 [1]. One can see that a PCB line impedance value, for example, calculated as 55 Ω can really be 45 Ω or 65 Ω. Thus, it is important to seek new ways to minimize sensitivity of critical characteristics of PCB transmission lines. Besides, proper tools for multiple, but quick and accurate, calculations of the characteristics are necessary.

With increasing requirements to electronics characteristics it is necessary to have transmission lines with more stable per-unit-length delay (τ) and characteristic impedance (Z). In turn, it leads to the necessity of detailed simulation and investigation of these characteristics.

One of the most widely used high-speed signal transmission lines is a microstrip line (MSL) [2]. The sensitivity of MSL characteristics has been a subject of extensive considerations since the appearance of MSLs and is still a matter of great importance. Particularly, variations of strip thickness and width as the most appropriate parameters to be controlled by a designer in practice have been considered in [3] and are being considered in [4]. (As opposed to sensitivity

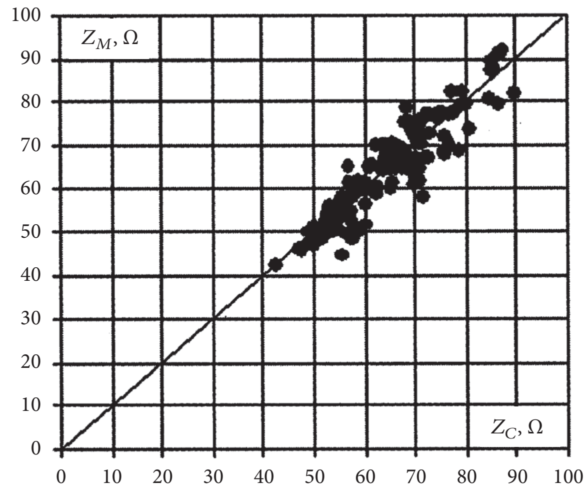


Figure 1: Comparison of measured (Z_M) and calculated (Z_C) impedance values for 186 test line samples of various cross-sections [1].

minimization, considerable modifications have also been proposed in order to increase the defined characteristics. For example, a slot in the ground plane increases the MSL characteristic impedance and can be properly used in a filter [5]. To accelerate the process of simulating such MSL characteristics, the analytic expressions have been proposed [6].)

However the possibilities to minimize the sensitivity of MSL characteristics are limited by the simplicity of the classical MSL construction. Therefore, various modifications of an MSL, such as suspended and inverted microstrip lines, allowing zero sensitivity of τ and Z, are considered. For example, a detailed study of sensitivity for a particular case of an air gap between a substrate and a ground plane has been considered [7]. A more general case of a nonair dielectric layer between a substrate and a ground plane has also shown possibilities to minimize the sensitivity to changes in the thickness of dielectric layers [8]. In the multilayer PCBs, the varieties of MSLs, for example, MSLs with polygons on different layers which allow obtaining a stable value of the τ, are used [9]. Similar possibilities are revealed in MSL with side grounded conductors located over the substrate [10] and buried in the substrate [11]. The possibility of minimizing the sensitivity arises from electric field redistribution in the layers of the air and the substrate. Similar phenomena occur in the case of placing an additional grounded conductor over a usual MSL and in the case of a totally shielded MSL [12].

To obtain necessary characteristics of a structure, it is required to carry out a multivariate analysis in the range of parameter variations. However, for a structure of an arbitrary cross-section, the quick and accurate expressions are not available. Therefore, it is necessary to use numerical methods, wherein the main costs fall on a multiple linear algebraic systems solution. In this case, depending on the type of the problem, only the matrix or the matrix and the right-hand side can be varied. In the matrix case we can write

$$\mathbf{A}_k \mathbf{x}_k = \mathbf{b}_k, \quad k = 1, 2, \ldots, m, \tag{1}$$

where $\mathbf{A}_k$ are nonsingular matrices, $\mathbf{b}_k$ are corresponding right-hand sides, k is a sequence number of linear system, and m is the number of linear systems to be solved. To solve sequence (1), iterative methods with preconditioning are often used. However, calculating the preconditioner and using it in solving sequence (1) are significantly different, compared to solving one linear system.

The first approach to solving sequence (1) is recomputing a preconditioner for each matrix of this sequence from scratch [13]. However, computational costs increase significantly, which does not make it effective. The second approach is based on the use of a frozen preconditioner, calculated from the first matrix of sequence (1) and used to solve subsequent linear systems. This approach has found wide application in solving nonlinear equation problems [14–16]. Obviously, this approach has less computational complexity, but in practice there are often situations when the solution of the current linear system cannot be obtained due to the stagnation of the iterative process. First of all, this is due to the fact that matrix-to-matrix changes of sequence (1) are significant and the application of a frozen preconditioner becomes ineffective. Therefore, the process of updating the preconditioner is widespread. The remaining approaches contain features of the two described. The third approach lies in updating the preconditioner obtained from the matrix of one of the systems (seed preconditioner), and repeated when necessary. This approach has proven itself in solving the sequences of shifted systems which emerge in problems of numerical optimization and solutions of nonlinear equations performed by the methods of Newtonian type [17–19]. Papers [20–22] were devoted to developing the approaches for updating incomplete LDL^T-decomposition of matrix $\mathbf{A}$, which is used to form a preconditioner. Then, these approaches were generalized on the case of nonsymmetric matrices with updating the preconditioner periodically or before solving the current system. The last approach is based on the adaptive use of information about the Krylov subspaces obtained on the previous steps (recycling of Krylov subspaces) [23–25]. Therefore, there exist appropriate algorithms which can be used (*per se* or after some additional modifications) to perform accelerated simulations of transmission line structures.

Thus, it is useful to analyze the results obtained as well as the techniques and the tools used for these studies. The aim of this paper is to propose a general approach to solving the complexity problem in electronics production process based on the summary of the recent studies devoted to minimizing the sensitivity of microstrip-like lines characteristics to variations of their parameters.

2. Structures and Approach for Investigation

Various modifications of the MSL under study are presented in Figures 2–4.

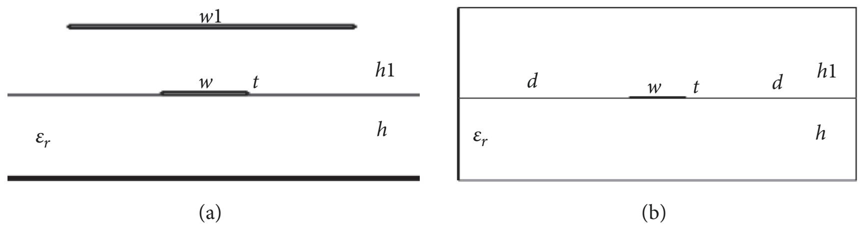


Figure 2: Cross-sections of covered (a) and shielded (b) MSLs.

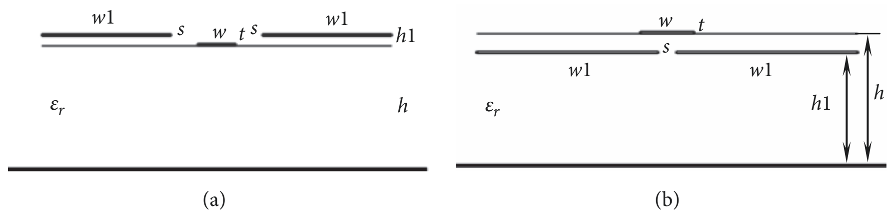


Figure 3: Cross-sections of MSLs with side grounded conductors in air (a) and dipped in substrate (b).

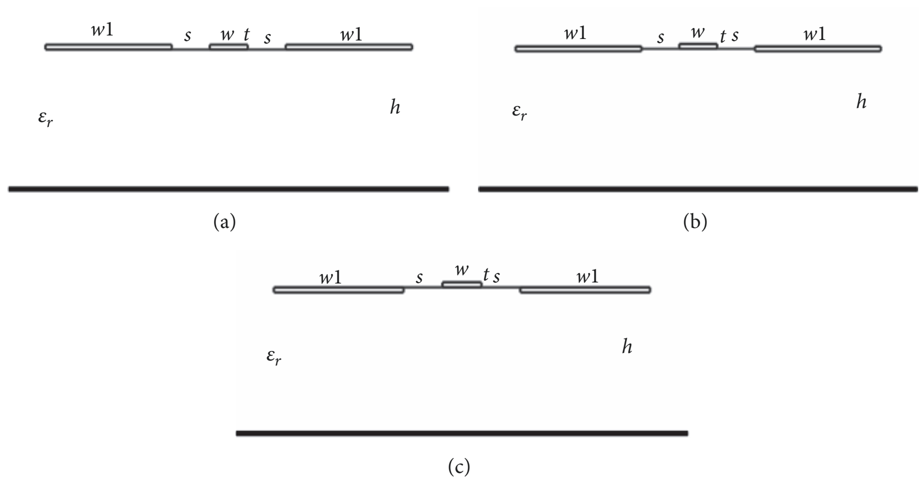


Figure 4: Cross-sections of MSLs with side grounded conductors above (a), among (b), and under (c) air–substrate boundary.

The values of the characteristics (τ and Z) of the investigated lines from Figures 2–4 were calculated by the known formulas:

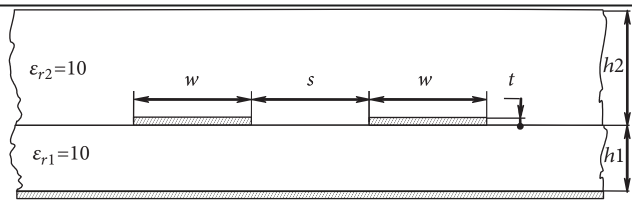
$$\tau = \frac{(C/C_0)^{0.5}}{v_0},$$
$$Z = \frac{1}{\left(v_0 \left(CC_0\right)^{0.5}\right)} \quad (2)$$

where v_0 is the speed of light in a vacuum; C and C_0 are signal strip diagonal entries of per-unit-length coefficient matrix of electrostatic induction in the real dielectric filling and in the air.

The investigation of a microstrip structure of various characteristics, especially in the first stage should be performed through simulation, as it is less costly and may be more accurate than measurements. In this regard, in this work, the construction of cross-sections and calculations are performed in the TALGAT system available to the authors [28]. Strict full-wave analysis of fields in the investigated lines is rather complicated. This is due to the inhomogeneity of the dielectric medium over the section of the line. As a result, part of the field is concentrated in the dielectric substrate and the rest in the air. Therefore, not pure TEM-mode but quasi-TEM-mode propagates in the lines.

Before using any software, one must validate it properly by using simulation and measurements. However, in case of coupled transmission lines, the off-diagonal coefficients of a per-unit-length matrix have large (up to 25%) error [29]. Therefore, one can use computations by several numerical methods. Indicative examples of such approach are shown in Table 1 [29]. It demonstrates the mentioned large measurement error and the close results of numerical methods. The method of moments (MoM) is the most widely used and tested method among them. Thus, we used the MoM implemented in the TALGAT system. In order to test it, we

Table 1: Results of simulation by Green's Function Method (GFM), Method of Moments (MoM) and Variational Method (VM) and measurement (pF/cm).



Size (mills) for $h1$=10, $h2$=20, t=0.5	Results	C_{11}	$-C_{12}$
w=40, s=10	GFM	5.61	0.77
	MoM	5.62	0.76
	VM	5.64	0.68
	Measured	5.59±0.06	0.62±0.15
w=20, s=10	GFM	3.78	0.70
	MoM	3.78	0.70
	VM	3.78	0.63
	Measured	3.69±0.04	0.38±0.10
w=10, s=20	GFM	2.66	0.29
	MoM	2.65	0.30
	VM	2.67	0.24
	Measured	2.64±0.03	0.20±0.05
w=10, s=10	GFM	2.77	0.59
	MoM	2.76	0.60
	VM	2.77	0.53
	Measured	2.75±0.30	0.48±0.12
W=10, s=5	GFM	3.00	0.97
	MoM	2.99	0.97
	VM	2.96	0.94
	Measured	2.95±0.03	0.92±0.23

computed the per-unit-length matrices of various structures, for which there exist published original and obtained results.

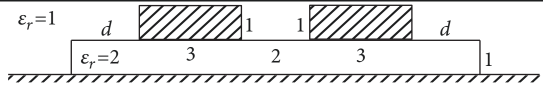
Firstly, we compared results for a simple case of 2 coupled strips on a substrate [26] shown in Table 2. However, we consider the cases of side dielectric walls becoming closer to side strip edges and the similar cases without side dielectric walls (Table 2). Maximum errors are 1.4% for diagonal and 8.1% for off-diagonal values. The coincidence is satisfactory.

Then, we considered the same 3 strips of various positions in a two-layer dielectric medium [27] (Table 3). Comparison of our results and the results obtained with the use of integral equation method showed maximum error 8.8% for **C** and 0.8% for **L** entries. The coincidence is also satisfactory for this more complex structure.

Thus, the performed comparisons showed satisfactory coincidence of the results and the relevance of the TALGAT system for computing per-unit-length matrices for structures of various complexities. Meanwhile, for final testing, one can compare a time response of a structure. There exist indicative and commonly available examples comparing the TALGAT system results with the measurement [30, 31] and electromagnetic analysis [32] results being omitted here.

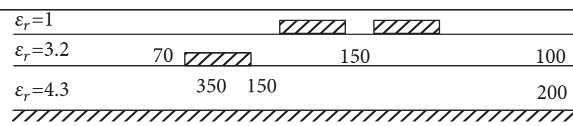
We are using several approaches to reduce the computational complexity of the analysis. The main feature of these approaches is the use of iterative methods. So, when solving the first linear system, we calculated a proper preconditioner. This preconditioner (frozen) is used to solve subsequent linear systems. At the same time, the use of the previous system solution as the initial guess is more preferable than the fixed initial guess [33]. However, as the differences between the matrices increase, the preconditioner efficiency decreases. Therefore, updating or recomputing the preconditioner is needed. We use the second approach. For this purpose we developed methods of adaptive recomputing preconditioner based on the threshold of the number of iterations [33], the average arithmetic complexity [34], and the average solution time [35]. Recomputation of the preconditioner is not necessary if the seed matrix for calculating the preconditioner has been selected properly. In this case, the choice of a seed matrix from the middle of the sequence linear systems allows us to accelerate the overall solution without recomputing the preconditioner. Another very simple way to accelerate the solution is to choose the solution order. So, it was shown that the reverse (from the highest value of the parameter being varied to the smallest) order comparing to the direct (from the lowest value of the parameter being varied to the largest) order is more preferable [36].

Table 2: Comparison of computed entries of matrix **C**.



d	Results	C_{11}		$-C_{12}$	
		Without walls	With walls	Without walls	With walls
6.0	Result [26], pF/m	92.36	92.05	8.494	8.473
	Our result, pF/m	91.11	91.11	9.162	9.162
	Error, %	−1.3	−1.0	7.8	8.1
4.0	Result [26], pF/m	92.44	92.14	8.506	8.485
	Our result, pF/m	91.15	91.14	9.167	9.168
	Error, %	−1.4	−1.1	7.7	8.0
2.0	Result [26], pF/m	92.40	92.10	8.539	8.517
	Our result, pF/m	91.15	91.08	9.179	9.182
	Error, %	−1.3	−1.1	7.5	7.8
0.5	Result [26], pF/m	91.44	90.50	8.595	8.565
	Our result, pF/m	90.73	89.88	9.185	9.184
	Error, %	−0.7	−0.7	6.8	7.2
0	Result [26], pF/m	89.68	87.97	8.603	8.569
	Our result, pF/m	89.34	87.68	9.146	9.146
	Error, %	−0.3	0.3	6.2	6.7

Table 3: Comparison of computed **C** (pF/m) and **L** (nH/m) entries for 3 strips of various positions in a two-layer dielectric medium.



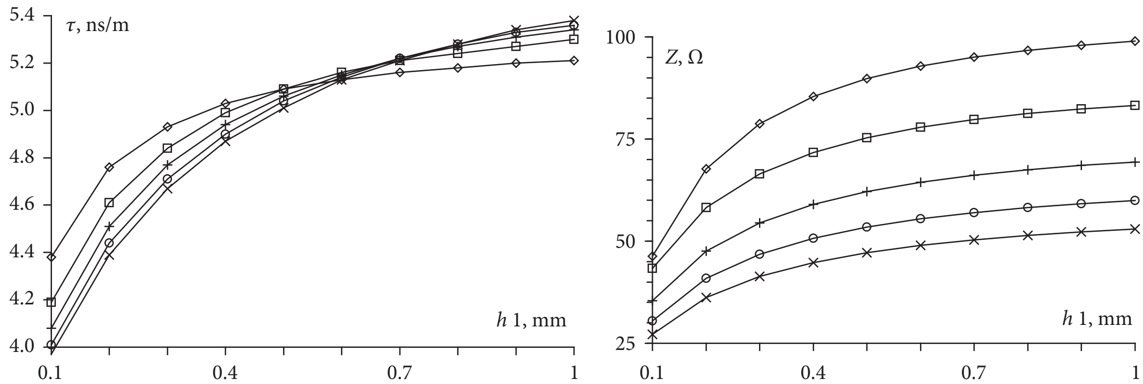
Results	C_{11}	$-C_{21}$	$-C_{31}$	C_{22}	$-C_{32}$	C_{33}
Result [27]	142.1	21.7	0.9	93.5	18.1	88.0
Our result	143.6	19.8	0.9	88.6	17.7	83.1
Error, %	1.1	−8.8	0	−5.2	−2.2	−5.6
Results	L_{11}	L_{21}	L_{31}	L_{22}	L_{32}	L_{33}
Result [27]	277.7	87.8	36.8	328.6	115.8	338.0
Our result	279.4	87.6	36.5	330.7	115.5	339.0
Error, %	0.6	−0.2	−0.8	0.6	−0.3	0.3

3. Results of Calculations

3.1. An MSL Covered with a Grounded Conductor and a Shielded MSL. Constant parameters for the line in Figures 2(a) and 2(b) are strip thickness t=18 μm, substrate thickness h=1 mm, and relative dielectric constant of the substrate ε_r=4.5 (fiberglass).

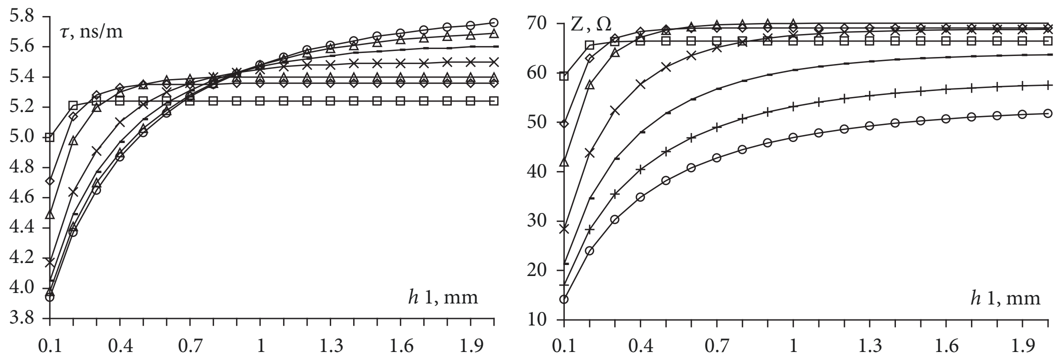
For Figure 2(a) dependencies of τ on the height grounded conductor ($h1$) above the substrate at different values of the strip width (w) are shown in Figure 5(a). A characteristic feature of the dependencies is their intercrossing. Thus, at the beginning of the range of $h1$, the increase of w decreases τ and at the end increases. In the middle of the range (at $h1$=0.5–0.8 mm) there will be a minimal (up to zero) sensitivity of τ to the variation of w. It is also remarkable that the sensitivity of τ to the variation of $h1$ decreases with the decrease of w. Similar dependencies for Z are shown in Figure 5(b). They increase monotonically and do not intercross.

For Figure 2(b), the characteristics were preliminarily simulated at a distance from the side walls to the strip (d) equal to w for w=0.1 mm for segment lengths of 10, 5, 2.5, 1.25 μm (with the uniform segmentation of the boundaries of conductors and dielectrics). The results analysis showed a consequent increase in the τ value with deviations of 0.4, 0.3, and 0.1% and a decrease in the Z value by 0.7, 0.4, and 0.1%, respectively. Subsequent calculations were performed with a segment length of 10 μm, providing an acceptable error of less than 0.7%. The dependencies of τ and Z on the height of the cover above the substrate ($h1$) at different values of w for the distance from the side walls to the strip d=w, 3w are shown in Figures 6 and 7. The analysis of the dependencies in Figures 6(a) and 7(a) shows that upon varying $h1$ in the



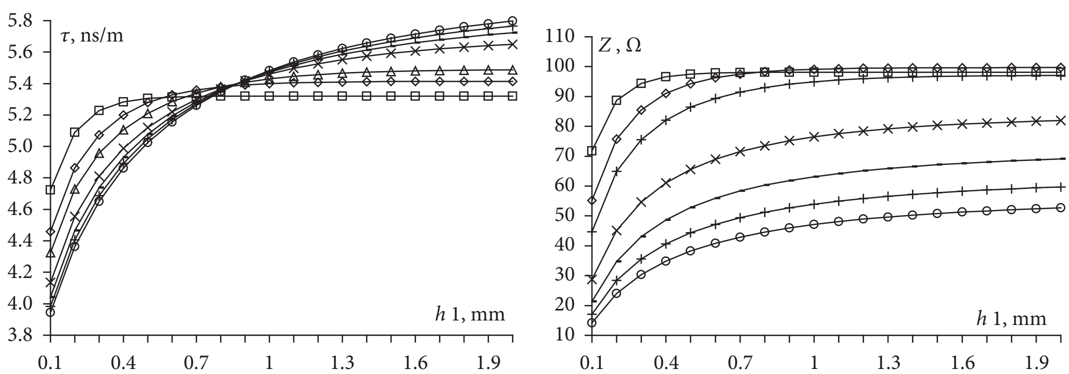
(a) (b)

Figure 5: Dependencies of τ (a) and Z (b) on $h1$ with w=0.3 (◊); 0.6 (□); 0.9 (+); 1.2 (○); 1.5 (×) mm for Figure 2(a).



(a) (b)

Figure 6: Dependencies of τ (a) and Z (b) on $h1$ with w=0.1 (□); 0.2 (◊); 0.3 (Δ); 0.6 (×); 0.9 (-); 1.2 (+); 1.5 (○) mm and d=w for Figure 2(b).



(a) (b)

Figure 7: Dependencies of τ (a) and Z (b) on $h1$ with w=0.1 (□); 0.2 (◊);0.3 (Δ); 0.6 (×); 0.9 (-); 1.2 (+); 1.5 (○) mm and d=3w for Figure 2(b).

entire range, when the strip is widest (w=0.6, 0.9, 1.2, 1.5 mm), the value of τ increases monotonically, and when the width of the strip is small (w=0.1, 0.2, 0.3 mm), the zero sensitivity of τ to the variation of $h1$ is observed, in almost entire range. Dependencies over w=0.6; 0.9; 1.2; 1.5 mm intercross at one point ($h1$=0.9 mm); i.e., at this point there will be zero sensitivity of τ to the change of w. As w decreases to 0.1 mm, the intercrossing point of the dependencies shifts to $h1$=0.2 mm. In Figures 6(b) and 7(b) the corresponding dependences for Z are shown. They behave similarly to the dependencies for τ, also showing the possibility of obtaining zero sensitivity to changes in $h1$ and w. This fact has special practical importance because the stability of Z is critical for many applications.

Consider the influence of the side walls on the calculated characteristics. Quantitative estimates can be done from the comparison of the relevant dependencies from Figures 5, 6, and 7. Meanwhile, the comparison with the dependencies for

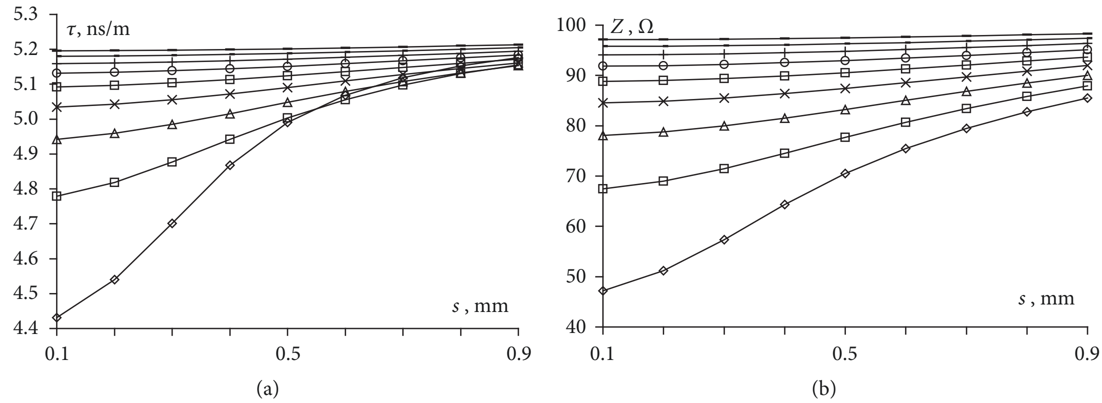


Figure 8: Dependencies of τ (a) and Z (b) on s with $h1$=0.1 (◊); 0.2 (□); 0.3 (Δ); 0.4 (×); 0.5 (□); 0.6 (○); 0.7 (+); 0.8 (-); 0.9(–) mm for Figure 3(a).

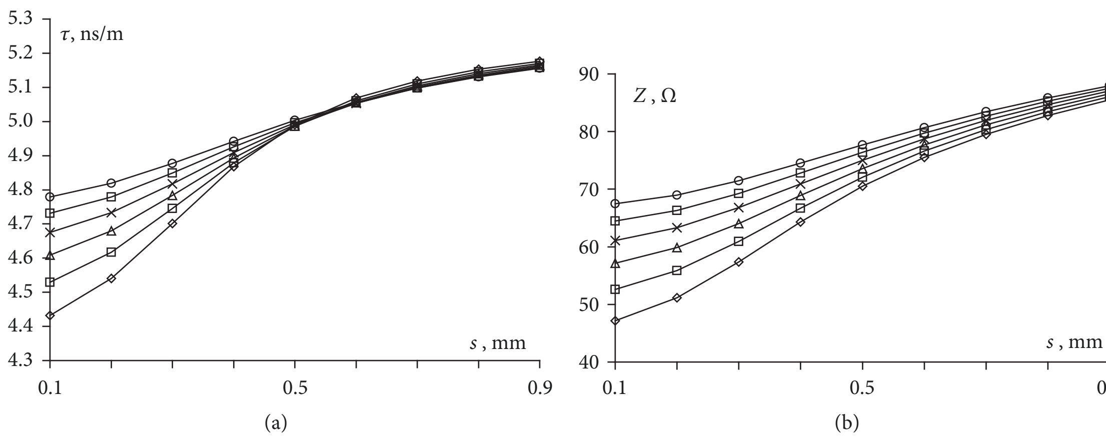


Figure 9: Dependencies of τ (a) and Z (b) on s with $h1$=0.1 (◊); 0.12 (□); 0.14 (Δ); 0.16 (×); 0.18 (□); 0.2 (○) mm for Figure 3(a)

the covered MSL (without side walls) of the same parameters allows us to assume that it is the presence of side walls, by increasing the edge capacitances, that gives the possibility of obtaining zero sensitivity of τ and Z over a wide range of values of $h1$.

3.2. MSLs with Side Grounded Conductors. Consider the results for various modifications of MSLs with side grounded conductors (Figures 3 and 4). To build these structures we chose the following cross-sectional parameters (they are close to typical): the width of the signal conductor is w=0.3 mm, the thickness of the signal and side grounded conductors is t=18 μm, the width of the side conductors is $w1$=1 mm, the thickness of the dielectric substrate is h=1 mm, and the relative permittivity of the substrate is ε_r=4.5.

In the TALGAT software we built the geometric models of the line cross-section and calculated (using the method of moments) the matrices (3×3) of per-unit-length coefficients of electrostatic induction, taking into account the dielectric as well as ignoring it. Calculations were performed, changing the distance ($2s+w$) between the side conductors located in the air, for $h1$=0.1–0.9 mm (with a segment length of 5 μm for Figure 3(a)). It can be seen from Figure 8 that with increasing s the values of τ and Z smoothly increase. At low values of $h1$ and s, changes in τ and Z are more pronounced, and an increase in $h1$ leads to an increase in the values of τ and Z. The approaching of the side conductors to the air–substrate boundary has a special effect on the characteristics of τ: for small values of $h1$, the characteristics intersect. Therefore, we performed similar calculations for $h1$=0.1–0.2 mm with a step of 0.02 mm (Figure 9). One can see a similar behavior of dependencies for small s. However, at s=0.5–0.9 mm, the minimum (close to zero) sensitivity of τ to the change in $h1$ is revealed, which can be used to obtain a stable delay.

For Figure 3(b) we performed calculations for the change of distance between the side conductors (s), dipped in the substrate, for the height of the side conductors $h1$=0.1–0.9 mm (Figure 10). It is seen that with the increase of s, the value of τ gradually decreases, while Z increases. At low values of $h1$, the changes of τ and Z are small, but the growth of $h1$ leads to an increase in the value of τ and a decrease in the value of Z, while at small values of s the changes of τ and Z are more significant. Additionally, we performed simulation with a smaller step near the air–substrate interface: for $h1$=0.8; 0.82; 0.84; 0.86; 0.88; 0.9 mm (Figure 11). The analysis of Figure 11 shows a similar behavior of dependencies, but it reveals its specific character as well. It is expressed in

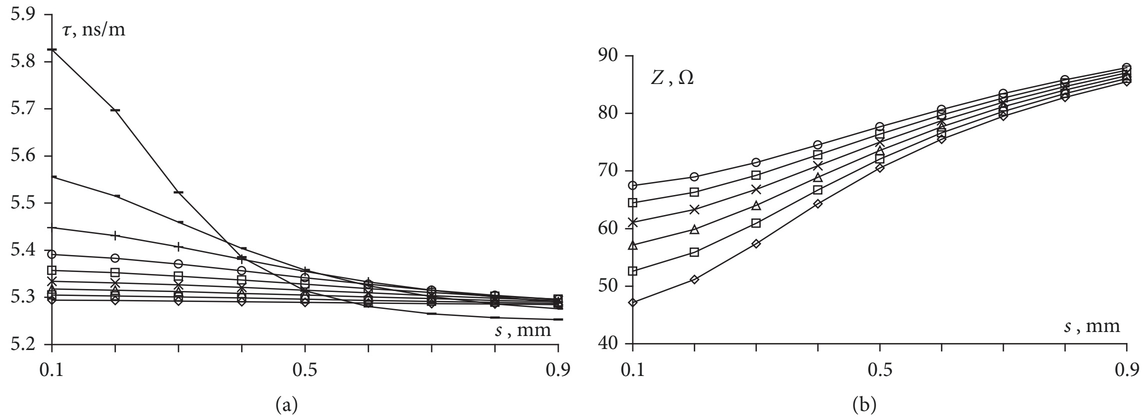


Figure 10: Dependencies of τ (a) and Z (b) on $h1$ with $h1$=0.1 (◊); 0.2 (□); 0.3 (Δ); 0.4 (×); 0.5 (□); 0.6 (○); 0.7 (+); 0.8 (-); 0.9(–) mm for Figure 3(b).

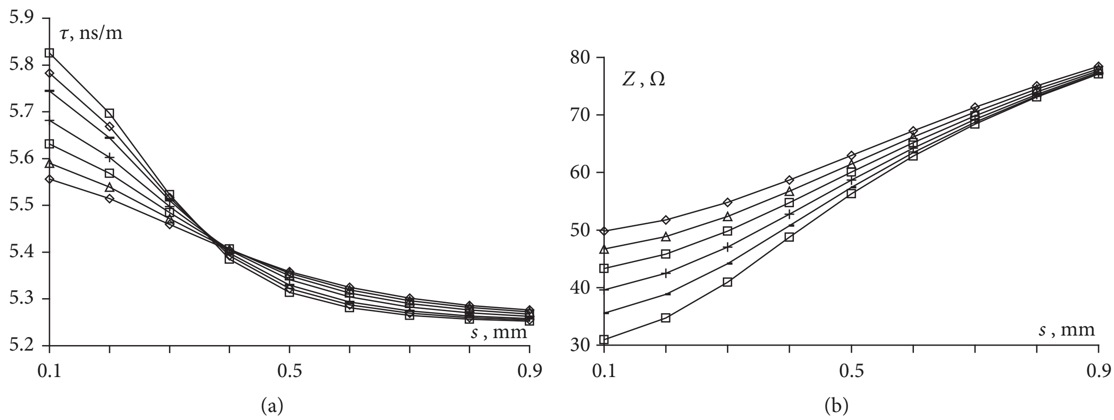


Figure 11: Dependencies of τ (a) and Z (b) on with $h1$=0.8 (◊); 0.82 (Δ); 0.84 (□); 0.86 (+); 0.88 (–); 0.9 (□) mm for Figure 3(b).

the increased influence of the side conductors when they approach the air–substrate interface for low values of s. When s=0.1 mm, the value of τ increases from 5.56 to 5.82 ns/m. We noticed that, for large values of s, the approaching of the side conductors to the air–substrate boundary does not increase but, instead, decreases the values of τ. When s=0.6 mm, this decrease is maximal and is from 5.33 ns/m to 5.29 ns/m. When s=0.38 mm, the change of $h1$ value in the whole range hardly ever changes the values of τ and, therefore, zero sensitivity of τ to changes of $h1$ is possible. Thus, we can obtain the required Z value in the range from 48 to 59 Ω by changing the value of $h1$.

As s increases, the values of τ (Figure 12(a)) and Z (Figure 12(b)) gradually increase, but the change of τ is much smaller. The deepening of grounded conductors reduces the sensitivity of τ to changes in s. The change of τ over the entire range of s is less than 2%. It can be assumed that with certain parameters of MSLs, their sensitivity can be reduced to zero. In this regard, in addition to t=18 μm, the values of τ and Z are calculated for typical values of the thickness of the conductors (t=35, 70, 105 μm) as s varies (Figures 13–15). Consider first the graphs for τ (Figures 13(a), 14(a), and 15(a)). With the increase of s, the value of τ smoothly increases, but not in all cases. Thus, the deepening of grounded conductors reduces the sensitivity of τ to changes in s, and even more, with increasing the thickness of the conductors, down to zero sensitivity of τ. It can be assumed that with certain parameters of MSLs, the sensitivity can be reduced to almost zero in a wide range of s values. For example, the value of τ for Figure 3(b) at t=35 μm (Figure 13(a)) is changed only by 0.8%. The graphs for τ at t=105 μm (Figure 15(a)) are also indicative, since the graph for τ, with the deepening of the lateral conductors, turns from monotonously increasing into monotonously decreasing. It is obvious that there is such a value of the deepening of the conductors, at which the graph for τ will look very much like a horizontal straight line in the maximum range of s values. The analysis of the graphs for Z (Figures 12(b), 13(b), 14(b), and 15(b)) shows a slight influence of the position of the lateral conductors. Thus, it becomes possible to choose the line parameters to get the required Z value with the minimum sensitivity of τ to the variations of s.

4. Conclusion

We have presented the systematic results of our study into the values of τ and Z of modified MSLs. Comparison of the

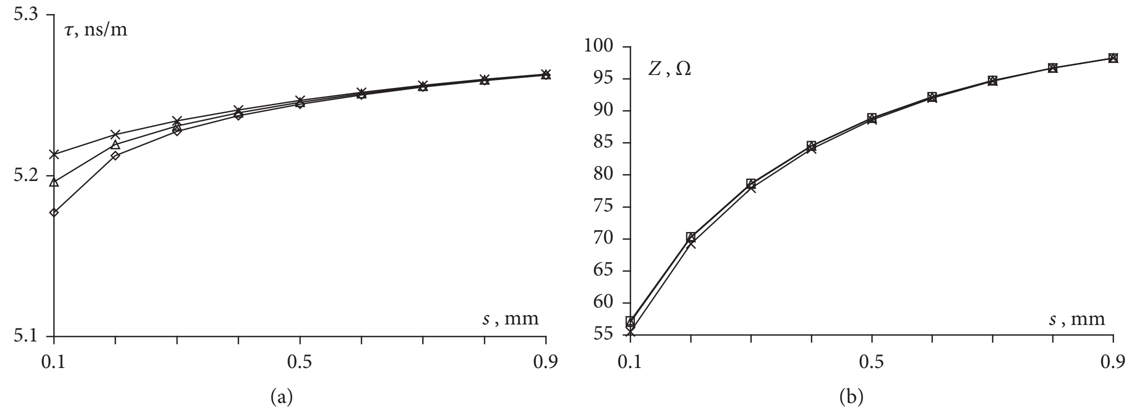


FIGURE 12: Dependencies of τ (a) and Z (b) on s for Figure 4 a (□), b (Δ), c (×) with t=18 μm.

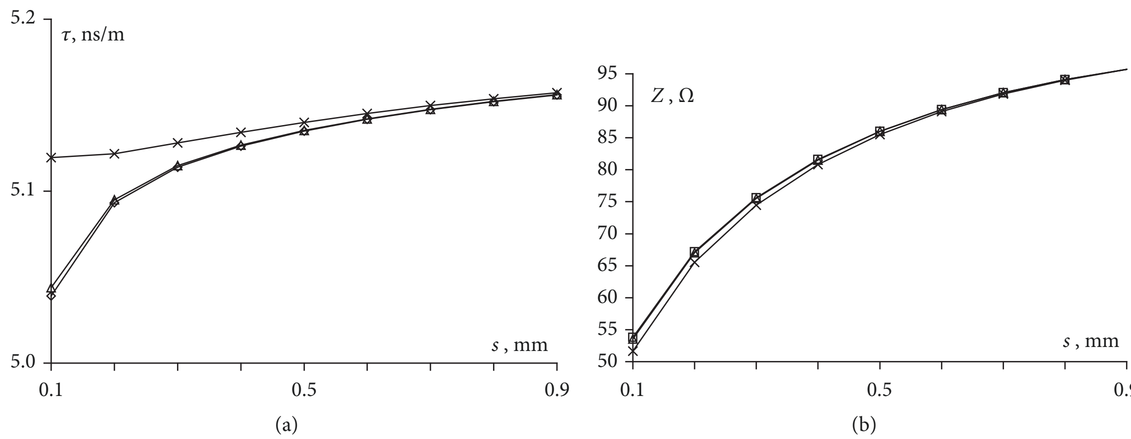


FIGURE 13: Dependencies of τ (a) and Z (b) on s for Figure 4 a (□), b (Δ), c (×) at t=35 μm.

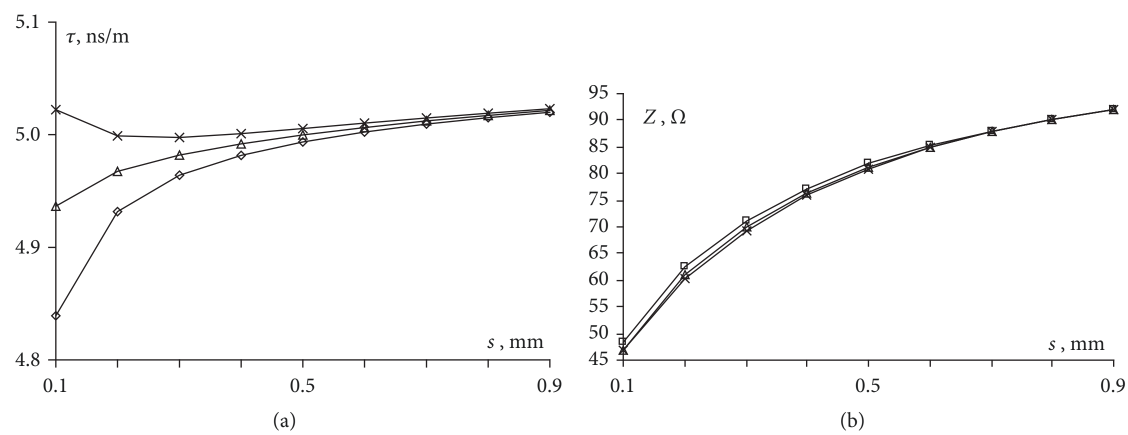


FIGURE 14: Dependencies of τ (a) and Z (b) on s for Figure 4 a (□), b (Δ), c (×) with t=70 μm.

MSL covered with a grounded conductor and the shielded MSL showed that the presence of side walls, by increasing the edge capacitances, allows minimal sensitivity in a wide range of upper conductor height values. For the MSL with side grounded conductors, their proximity to the air–substrate interface has a special influence on the characteristics under study. In particular, it becomes possible to select the line parameters to get the required Z value with the minimum sensitivity of τ to the change in s. In addition, we revealed the possibility of zero sensitivity of τ to the change in the distance between the grounded conductors and the air–substrate interface when a given value of Z is obtained.

The presented results have been obtained for particular values of line parameters. However, it is easy to obtain similar

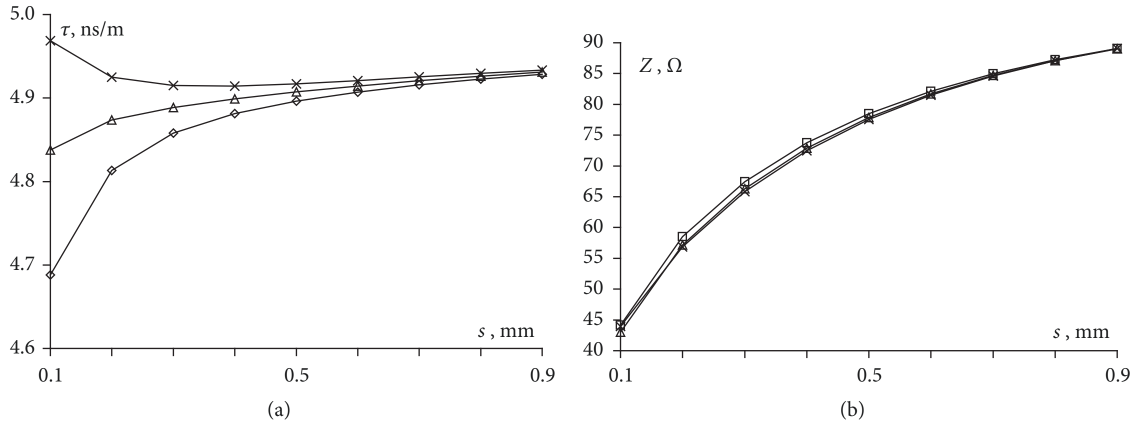


FIGURE 15: Dependencies of τ (a) and Z (b) on s for Figure 4 a (□), b (Δ), c (×) at t=105 μm.

dependencies for other values of the parameters and even other parameters. Besides, transmission lines with arbitrary number and shapes of conductors and dielectrics can be studied easily [28] to manufacture transmission lines with stable characteristics.

For multiple calculations, a lot of described accelerations of linear system solutions can be effectively used. In this paper, for quick estimations, we have used calculations of transmission line parameters only. However, for more comprehensive analysis, you can calculate the frequency or time response and use optimization by genetic algorithms similarly to [37].

Thus, taken together, for the first time, the above-mentioned techniques form a general approach to solving complexity problem in the electronics production process through the reduction of sensitivity of transmission line characteristics to their parameter variations. Versatility of the approach allows solving a wide range of tasks similar to considered examples.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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