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Extracting R, L, G, C Parameters of Dispersive Planar Transmission Lines from Measured S-Parameters Using A Genetic Algorithm

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Abstract—Signal integrity (SI) analysis of printed circuit boards for high-speed digital design requires information on the per-unit-length R, L, G, C parameters of the transmission lines. However, these are not always available when the property of the dielectric medium used in the board is unknown. A method to extract R, L, G, and C parameters from parallel-plate and strip transmission line geometries is proposed. It is based on measured scattering parameters and analytical modeling. A genetic algorithm (GA) is used to optimize the extraction by minimizing the frequency domain discrepancy between an objective function, which is the measured scattering matrix parameter, $|S_{21}|$, and a GA model based on transmission line theory. The extracted R, L, G, and C parameters are then used in a SPICE model for simulation. Good agreement has been achieved in the reported results.

Keywords—signal integrity; transmission line; scattering matrix parameter; R,L,G,C extraction; genetic algorithm

I. INTRODUCTION

Signals propagating in modern digital circuits are getting faster and faster. When the on-board frequencies are above hundreds of MHz, or especially in the GHz range, traces on the printed circuit boards (PCBs) no longer behave as simple conductors, but instead exhibit high-frequency effects and behave as transmission lines that are used to transmit or receive electrical signals to or from neighboring components [1]. An accurate simulation of high frequency effects such as dielectric dispersion, and skin effect loss on transmission lines is necessary for high-speed digital design. Otherwise, improper modeling of these transmission lines will result in poor SI analyses. Therefore, exact per-unit-length R, L, G, and C parameters (RLGC) of transmission lines are needed for signal integrity analysis. Though many commercial tools are available to extract the RLGC parameters, the condition is that the property of the dielectric medium must be known first. However, that is not always case. For example, FR-4 is a common fiberglass/epoxy dielectric material used in PCBs. If dispersion is not considered in this kind of material, the dielectric constant of the permittivity is usually in the range of

2 to 5. But for a specific PCB, the exact permittivity is unknown. Furthermore, if the dispersion needs to be considered in the PCB, such as a Debye or a Lorentzian model, the detailed dielectric properties of the material are even harder to find in the literature or from manufacturers. This is because the dielectric properties of the FR-4 materials vary by manufacturer, process technologies, and the constituents contained in the materials, as well as environmental factors, such as temperature and moisture. It is necessary to develop an efficient method to extract RLGC parameters from a set of measured data. In this paper, a new technique to extract the per-unit-length parameters is proposed. It is associated with the scattering parameter (S-Parameter) measurement, and an analytical transmission-line model. A genetic algorithm is used to minimize the discrepancy of the measured S-Parameters and the evaluated model results using a GA. The best RLGC parameters are extracted when the discrepancy is minimized.

The RLGC parameters depend on constitutive parameters of the dielectrics used in the PCBs. These dielectrics may be dispersive; thus, the corresponding per-unit-length parameters are frequency dependent in the frequency range of interest. In the method proposed herein, the per-unit-length parameters are first assumed to be independent of frequency, and extracted. Then the extracted RLGC parameters are used in the analytical model to estimate the S-Parameters. If the discrepancy between the simulation and the measurement is less than the desired difference, further frequency dependent RLGC parameters will not be extracted. Otherwise, the dispersion will be taken into account, and the frequency dependent RLGC parameters are extracted. In the two studied cases, stripline and parallel plate line, only the frequency independent RLGC was extracted for the stripline due to the discrepancy between the measured and the analytical model being S-Parameter less than 0.2 dB. This was due to the low-loss material used. However, both frequency dependent and independent RLGC parameters were considered for the parallel plate transmission line case. In this case, the maximum difference of the measured S-Parameter and

analytical model in the non-dispersive case was approximately 1.5 dB, which meant the non-dispersive assumption was inadequate, and the dispersion must be taken into account.

The GA model used in the RLGC parameters extraction is based on transmission line theory. The detailed geometry information of the parallel plate transmission line and stripline was used to estimate the reasonable initial ranges of the RLGC parameters for extraction. The practical line length, or the line length with a minor perturbation to compensate for measurement error, was used in the GA model as the transmission line length. The port influence in the measurement due to the electrical length was removed by calibration with port extension. Other influences (such as fringing fields) were ignored in the model, which was reasonable, since the parallel plate test board met the requirement given in [2], and the stripline was embedded in a large PCB.

II. APPLICATION OF A GENETIC ALGORITHM

Genetic Algorithms (GAs) are search techniques based on the mechanics of natural selection and natural genetics [3]. They belong to the class of stochastic techniques for global search and optimization [4]. Most of the stochastic search methods deal with a single solution, while GAs operate on a population of solutions. When compared with the three major traditional optimization techniques, hill climbing optimization techniques, enumerative techniques, and random search techniques, the GAs have the advantages of being robust, efficient, and flexible. The hill climbing search techniques are based on the assumption that the problem domain being searched is continuous and the first order derivatives of the functions used to represent the problem in the search domain exist. This kind of search technique is based only on the local gradient in the search space; therefore, getting stuck in a local minimum is the major drawback in this sort of search method if the problem domain is multimodal. The enumerative search techniques try to find the optimum solutions in the problem space by point (variables) to point (possible solutions) mapping. This class of search method is inefficient when the problem space (system with finite variables) is large. If the problem space is continuous, it is impossible to use this kind of optimization method. Random search techniques are simple search methods characterized by randomly finding problem solutions in the search domain. There is no relationship between the previous searched results and the current search process. It is clear that the random search methods are also inefficient. The GAs, however, are a kind of random search, but they are associated with the directions and chances in the problem space from the previous search results, and, they are, therefore, efficient. In addition, the optimum solutions from GAs are based on entire populations. A local minimum is not a problem in the GA methods, which causes the GA to be robust. Furthermore, some physical rules in a specific case can be implemented in the GA model readily, which makes GAs more flexible in solving practical optimization problems.

The GA model was built up based on transmission line theory for the RLGC parameters extraction. The measured S-parameter, $|S_{21}|$, was the objective function. Real-valued vectors were used to represent the population in the search domain. The advantage of using real-valued representations is

that the GA works much quicker with a real-valued representation rather than with a binary representation, and the representation is in the same format as the problem solution to be studied. The non-dispersive initial states for the parallel plate transmission line and stripline are given in Table 1. If the dielectric dispersion is taken into account, the shunt conductance $G(f)$ can be expressed as [5]

$$G(f) \equiv G_0 + \frac{f}{\sqrt{1 + \left(\frac{f}{f_{gd}}\right)^2}} G_d, \quad (1)$$

where the G_d models the power loss due to the rotation of dipoles under the alternating field, and G_0 models the shunt current due to free electrons in imperfect dielectrics. The cutoff frequency f_{gd} indicates that the power loss becomes significant in dielectric materials when operation frequencies are above the f_{gd} . The per-unit-length resistance can be approximated as [6]

$$R(f) \equiv R_0 + \sqrt{f} (1+j) R_s, \quad (2)$$

when skin effect is considered, where R_0 is the DC resistance, and, R_s is the skin effect loss. The initial state for the parallel plate transmission line with the consideration of dielectric dispersion and skin effect loss is given in Table 2.

TABLE I. NON-DISPERSIVE INITIAL STATES FOR PARALLEL PLATE TRANSMISSION LINE AND STRIP TRANSMISSION LINE

Line Type	Initial RLGC range without dispersion			
	R (Ω/m)	L (H/m)	G (S/m)	C (F/m)
parallel plate	0.1 ~ 50	$10^{-9} \sim 10^{-6}$	0.001 ~ 0.9	$10^{-13} \sim 10^{-9}$
stripline	0.1 ~ 100	$10^{-10} \sim 10^{-7}$	$10^{-3} \sim 0.5$	$10^{-14} \sim 10^{-10}$

TABLE II. DISPERSIVE INITIAL STATES FOR THE PARALLEL PLATE TRANSMISSION LINE

Initial RLGC range with dispersion					
R (Ω/m)	R_s ($\frac{\Omega}{m \cdot \sqrt{Hz}}$)	L (H/m)	G_0 (S/m)	G_d ($\frac{\Omega}{m \cdot Hz}$)	C (F/m)
0.01 ~ 50	$10^{-6} \sim 10^{-1}$	$10^{-9} \sim 10^{-6}$	0.001 ~ 0.9	$10^{-13} \sim 10^{-9}$	$10^{-12} \sim 10^{-9}$

Operators, which are associated with the format of the representation, execute the initialization, selection, recombination, and mutation for those individuals in the search pool. The initialization includes using real-valued vectors to represent each variable set over the initial range,

which means to randomly discretize the continuous range to discrete real-valued vectors, assigning zero fitness to each individual to avoid the introduction of bias into the search pool, and initializing other variables in the GA model. The roulette-wheel selection method was used in the extraction since it is the simplest selection method [7]. The fitness was then mapped to the selection probability. Randomly generated data determined which individual was selected according to the selection probability. The higher the fitness value of each individual, the more chance of the individual staying in the search pool for generating offspring. The advantage of the roulette-wheel selection method is zero bias, while the disadvantage of the method is not generating the minimum spread. The discrete recombination method was used in each individual for randomly exchanging variable values based on an equal probability for each variable [8]. After the recombination, the real-valued mutation method was applied to the variables in the individual for adding random perturbation to achieve a better solution [9].

A fitness function is used to create and assign fitness for each individual. The fitness value indicates how good the individual is at competing in its environment. The fitness function was in the format of $1/(\text{abs}(\text{delta})+\eta)$, where the $\text{delta}=\Delta(f)$ was the discrepancy between the objective function and the evaluated S-Parameter for each individual at current frequency f , and η [dB] was the desired accuracy. In addition, the fitness for each variable was also created in the search process associated with the fitness of the individual proportionally, and it was updated during the search procedure. The variable fitness was a more direct in showing the competitiveness of each variable within the variable set. Two parallel mechanisms for stopping the search procedure were implemented in the two studied cases. One mechanism was connected to the desired accuracy η . The criterion of the S_{ij} parameter restoration at the frequency f was

$$\Delta(f) = \left| |S_{ij}^m(f)| - |S_{ij}^e(f)| \right| < \eta, \quad (3)$$

where the $|S_{ij}^m(f)|$ was the amplitude of the measured S-parameter, while the $|S_{ij}^e(f)|$ was the amplitude of the evaluated S-parameter from the analytical GA model. The $|S_{ij}^e(f)|$ was estimated using the formulas given in [2] as

$$|S_{21}| = 20 \log_{10} \left| \frac{2V_0^+(1+\Gamma_l)}{V_g} \right|, \quad (4)$$

where

$$V_0^+ = \frac{V_g Z_{in}}{(Z_{in} + r)(e^{-\gamma z} + \Gamma_l e^{\gamma z})}, \quad (5)$$

$$Z_{in} = Z_0 \frac{r + Z_0 \tanh(-\gamma z)}{Z_0 + r \tanh(-\gamma z)}, \quad (6)$$

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}}, \quad (7)$$

$$\Gamma_l = \frac{r - Z_0}{r + Z_0}. \quad (8)$$

Here r is the resistance of the source and the load of the measurement system. If the discrepancy between the objective function and the search result is in the desired range, then the search procedure stops, and, the expected RLGC parameters are extracted. Otherwise, the search continues until the criterion is met. If the η is not chosen appropriately in (3), then the search will never stop. To solve this problem, an alternative approach is to assign a generation number in the initialization. If the search process reaches the defined generation number, no matter whether the criterion is met or not, the search procedure is terminated. If all the variables are convergence, then the possible best parameters are extracted. Otherwise, the generation number should be increased, and a new search needs to be launched. The above step needs to be repeated again and again until all the variables converge. The program flow chart of the GA is shown in Figure 1. The average fitness curve for the parallel plate transmission line is given in Figure 2. Figure 3 shows the fitness curve of the per-unit-length capacitance at 9th generation in the parallel plate line case without consideration of dispersion, and Figure 4 gives the convergence curve of the capacitance.

The extracted RLGC parameters without taking into account dispersion for the stripline and the parallel plate transmission line are given in Table 3. Table 4 gives the extracted RLGC parameters with consideration of dielectric dispersion and skin effect loss for the parallel plate transmission line.

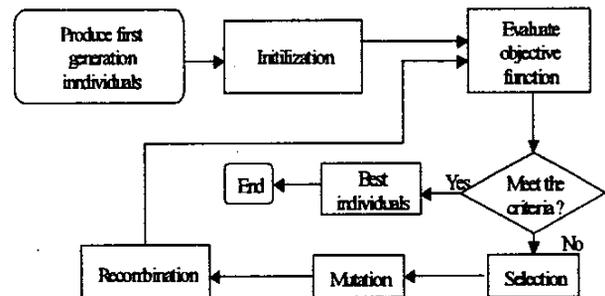


Figure 1. GA program follow chart.

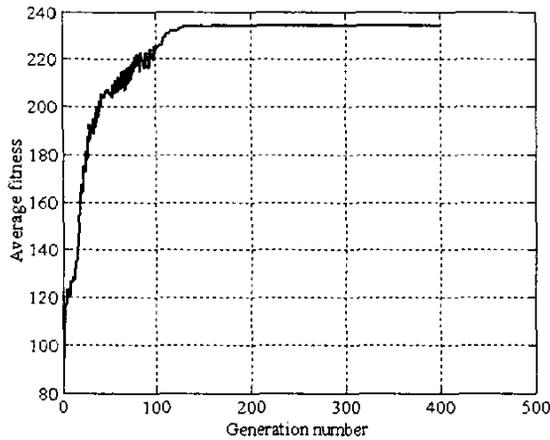


Figure 2. Average fitness for the parallel plate case without dispersion consideration.

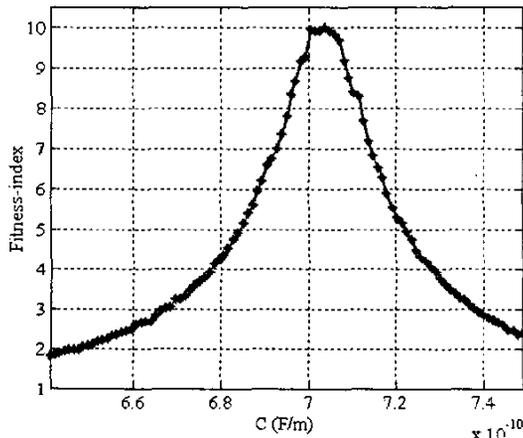


Figure 3. Fitness curve of the per-unit-length capacitance for the parallel plate transmission line without dispersion consideration at 9th generation.

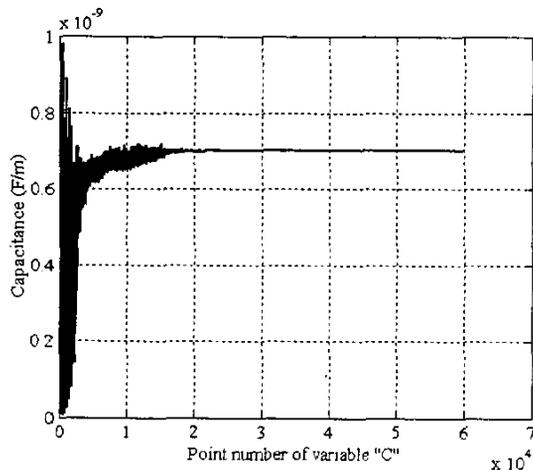


Figure 4. Convergence curve of per-unit-length capacitance of the parallel plate transmission line without dispersion consideration.

TABLE III. EXTRACTED NON-DISPERSIVE RLGC PARAMETERS FOR PARALLEL PLATE TRANSMISSION LINE AND STRIP TRANSMISSION LINE

Line Type	Extracted RLGC			
	R (Ω/m)	L (H/m)	G (S/m)	C (F/m)
parallel plate	21.31	6.519×10^{-8}	0.1218	7.030×10^{-10}
stripline	6.3043	5.737×10^{-9}	9.115×10^{-3}	9.000×10^{-12}

TABLE IV. EXTRACTED DISPERSIVE RLGC PARAMETERS FOR THE PARALLEL PLATE TRANSMISSION LINE

Extracted RLGC with dispersion					
R_0 (Ω/m)	R_s ($\frac{\Omega}{m \cdot \sqrt{Hz}}$)	L (H/m)	G_0 (S/m)	G_d ($\frac{\Omega}{m \cdot Hz}$)	C (F/m)
0.2273	2.028×10^{-5}	6.531×10^{-8}	0.1004	5.6×10^{-11}	1.17×10^{-10}

III. MEASUREMENT AND SIMULATION

Two cases were investigated. The first case was a stripline transmission line with a high-quality, low-loss FR-4 dielectric spacing. The dimensions of the test board are given in Figure 5. The $|S_{21}|$ of the stripline was measured using an HP 8753D network analyzer over the frequency range of 700 MHz to 5 GHz. The port influence in this case was deimbed by TRL calibration [10]. A SPICE simulation was done using the extracted RLGC parameters given in TABLE III. The $|S_{21}|$ comparison of the measurement and simulation is shown in Figure 8. The maximum discrepancy over the frequency range of interest is less than 0.2 dB. The agreement is sufficient for engineering purposes, and the assumption of neglecting the dielectric dispersion and skin effect is reasonable in this case.

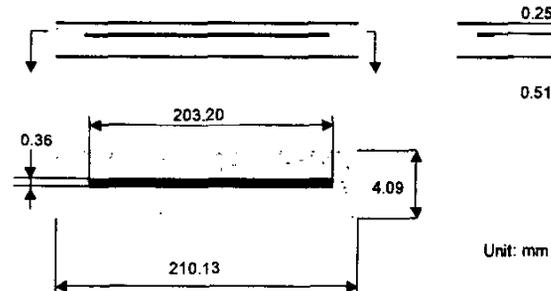


Figure 5. The dimensions of the stripline test board.

The second case was the parallel plate transmission line with the dimensions of $71.36 \times 19.80 \times 1.25$ mm³. The dielectric spacing with FR-4, between the two copper sheets is 1.05 mm, and the thickness of the trace is 0.1 mm. The test board is shown in Figure 6. A network analyzer, HP 8720ES, was used to measure the $|S_{21}|$ over the frequency range of 100 MHz to 5 GHz. The port influence due to the electric length was eliminated by port extension in the calibration. A SPICE simulation was performed using the extracted non-dispersive RLGC parameters, which are given in TABLE III. The $|S_{21}|$

comparison between the measurement and simulation is shown in Figure 8. The maximum difference, which is approximately 1.5 dB, occurs at frequencies above 4 GHz. The assumption that the RLGC parameters are frequency independent may be not adequate in this case. Then the dielectric dispersion and skin effect loss was taken into account, and the RLGC parameters were extracted with dispersion, which are given in Table IV. The SPICE modeled $|S_{21}|$ using the extracted dispersive parameters and the measured $|S_{21}|$ are given in Figure 9. The maximum error in this case is less than 0.5 dB.

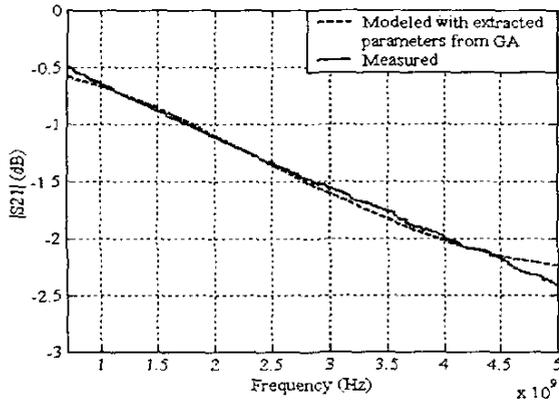


Figure 6. The $|S_{21}|$ comparison of measurement and H-spice simulation using the extracted RLGC without dispersion for the stripline.

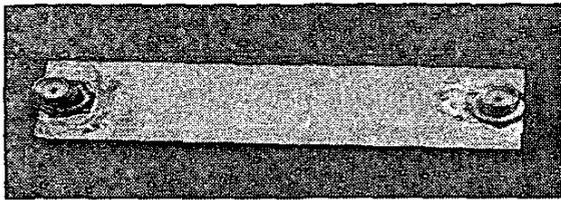


Figure 7. The parallel plate transmission line test board.

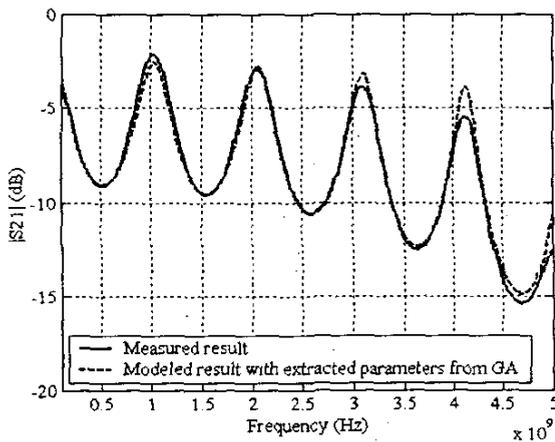


Figure 8. The $|S_{21}|$ comparison of measurement and simulation using the extracted RLGC without dispersion for the parallel plate transmission line.

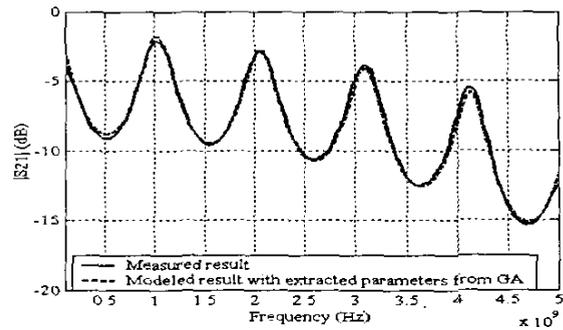


Figure 9. The $|S_{21}|$ comparison of measurement and H-spice simulation using the extracted RLGC parameters with dispersion for the parallel plate transmission line.

IV. CONCLUSION

A method for extracting RLGC parameters for stripline and parallel plate transmission line was developed, which is associated with the transmission line theory and S-Parameter measurement. Good agreement between the measurement and the H-spice simulation by using the extracted parameters has been achieved. This method is efficient in extracting the RLGC for transmission line (parallel plate line and stripline) when the exact properties of the dielectric medium are unknown. If the reasonable initial ranges of RLGC can be estimated without the detailed geometry information of the transmission line, the dimensions of the geometry are not even required except for the line length. This approach is very useful for building equivalent circuit models for signal integrity analysis. In practice, S-Parameter and the transmission line length are easy to obtain; however, the exact thickness of the dielectric spacing and the metal are not always available.

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