Design of RF and Wireless Packages Using Fast Hybrid Electromagnetic/Statistical Methods

Nathan Bushyager[1], Lara Martin[2], Shahriar Khushrushahi[1], Serkan Basat[1], and Manos M. Tentzeris[1]
[1]School of ECE, Georgia Institute of Technology, Atlanta, GA 30332-0250, U.S.A.
[2]Motorola, 8000 W. Sunrise Blvd., Plantation, FL 33322, U.S.A.
nbushyager@ece.gatech.edu

Abstract

A method for the design of packaging elements using a combination of electromagnetic simulation and statistical modeling techniques is presented. In this paper, finite-ground coplanar waveguide (FG-CPW) line coupling is addressed. The electromagnetic performance of two FG-CPW lines in parallel is determined with FDTD. The results of these simulations are analyzed using the design of experiments (DOE) and response surface modeling (RSM) techniques. The result is a statistical model that can be used to determine the line geometry based on performance requirements.

Introduction

Modern RF microsystems require increasingly higher levels of integration to create compact modules that incorporate the maximum amount of functionality. One method of accomplishing this is to place progressively more circuit components in the package. These components are placed in very close proximity and their interaction is inevitable. Crosstalk and coupling between closely spaced lines can have a catastrophic effect on the performance of a circuit. It is imperative that this coupling be quantified so that its effect can be accounted for in design. One common type of line used in these circuits is the finite-ground coplanar waveguide (FG-CPW)[1]. This paper explores the coupling between two finite-ground coplanar waveguides placed in parallel and quantifies the effect based on the circuit parameters using a methodology that integrates simulation and statistical tools.

Two identical, parallel, finite-ground coplanar waveguides can be characterized by five parameters, the width of the signal line, the distance between the signal line and the ground plane, the width of the ground plane, the spacing between the lines, and the height of the substrate. By comparing the performance of configurations generated by varying these parameters, the effect of each parameter can be determined. The number of cases required by varying these parameters can be large and their fabrication can be time consuming and expensive. In order to reduce this, these cases can be supplemented by simulation. By using an accurate simulator, such as the full-wave finite-difference time-domain technique (FDTD)[2], which has been shown to effectively model the topology performance in a wide frequency range[1], the parameter variation can be carried out numerically in a significantly quicker and inexpensive way. Statistical techniques can then be applied to the simulation results to develop accurate and highly efficient models that can predict performance based on any combination of parameters in a design space.

The hybrid design procedure for this investigation begins with identifying the parameters to be varied and determining the design space, that is, the ranges for the variation. The design space of the parameters has to be chosen such it includes the fabrication value range while providing sufficient variation in performance. In the case of the parallel FG-CPW lines, the parameter of interest is the signal coupled to one line when the other is excited (parasitic crosstalk). The results of these FDTD simulations are then used in design of experiments (DOE)[3] and response surface modeling (RSM)[4] statistical methodologies in order to develop a model that explains the effect of each parameter on the performance of the circuit.

This proof of technique is useful in a number of ways. First, it allows the interaction of circuit interconnects used in SOP and SOC geometries to be characterized in terms of their geometrical and material parameters in a swift manner. Furthermore, the technique can be applied to more complex wireless transceiver packages that can be extremely difficult to optimize, even in electromagnetic simulation. This allows the designer to optimize results from highly accurate electromagnetic simulation techniques with powerful statistical methodologies and apply them to highly-integrated RF structures using diakoptics approaches.

Design Structure

The structure analyzed in this paper is presented in Fig.1. This relatively simple structure appears in many circuits. When two lines are positioned in close proximity, parasitic coupling can be difficult to predict. Classical CPW configurations assume that the ground planes are infinite, though in this example they are significantly thinner (finite-ground) when compared to the width of the signal lines. This can lead to incomplete shielding between the lines and neighboring components and increase parasitic effects.

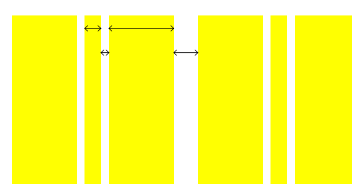

Fig.1 Diagram of parallel FG-CPW lines demonstrating relevant line parameters

In order to model the interaction of this device through simulation, the ranges of the line parameters must first be determined. The parameters of interest are identified in Fig.1, S is the width of the signal line, W is the width of the gap between the signal and ground, G is the ground width, and D is the distance between the lines. The design space of the parameters used for the simulation was chosen such that it represented physically realizable values.

The process chosen to simulate is a polyimide thin film over silicon. The silicon substrate is 500µm thick with a 20µm layer of polyimide on the surface. The silicon is thick enough for small variations in thickness to have no effect on the field penetration. The polyimide thickness, however, was modeled as a fifth parameter, H.

The design space for parameters H and the parameters shown in Fig.1, that is, W, G, S, and D, was defined. The parameters W and G are normalized to to the value of S, and thus a fixed value of S at 42µm was chosen. G was chosen to range from 2 to 6 times S (84-252 µm), and W from .285 to 1 times S (12-42 µm). The parameters are represented in this way to allow the variation of W and G to appropriately affect the line impedance and shielding, respectively. D was varied from 0 to 24µm and H from 10 to 30µm, to show a range where these parameters are relevant. The S-parameters as determined by the simulation are the response for the statistical models.

For the development of statistical models based on response values from deterministic simulation, variation of all parameters was statistically simulated. All parameters were assumed to be physically realizable within a tolerance of $\pm$ 2 µm, based on a 3σ process. Specifically, the values of the parameters were randomly generated assuming means equal to the nominal target and standard deviations equal to 0.6667 µm for the centerpoints of the DOE and RSM experimental designs.

The procedure used in the development of the statistical models that would predict S-parameters over the defined design space for D, G/S, W/S, and H is shown in Fig.2.

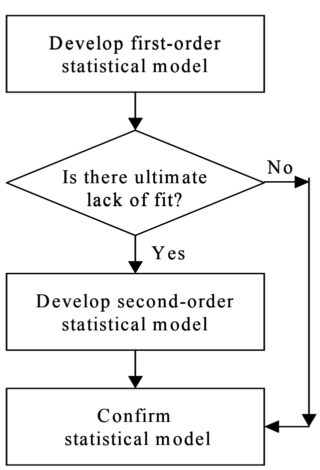

Fig.2 Procedure for statistical model development

To develop the first-order statistical model, a 2^4 DOE was performed. The DOE first-order model was reduced to identify and consider only significant parameters. The model was then checked for an ultimate lack of fit, that is, a lack of fit that could not be alleviated by transformation of S-parameter response. If an ultimate lack of fit was found, curvature in the parameters would be suspected and would require further model development. In this case, an RSM second-order model would be investigated. In particular, to develop a rotatable model for the defined design space, an inscribed, rotatable CCD (central composite design) would be investigated. Once either the first-order models or second-order models were validated for the prediction of the S-parameters over the defined design space, the final statistical models were confirmed.

Electromagnetic Simulation

The electromagnetic simulations were performed using an in-house parallelized full-wave FDTD simulator. For each example case, a simulation using both an even and odd mode excitation was used in order to eliminate parasitic effects due to common modes between the lines. In addition, a thru line simulation was required for each case. In total, 3 simulations were required for each case, therefore a total of 54 simulations were performed for the DOE and 60 were performed for the RSM. The execution time required on an 8 node dual Athlon MP 1800 Linux cluster was approximately 40 minutes per simulation.

The simulation output was used to determine the S-parameters of the system, which conform to the port definition presented in Fig.1. The S-parameters for two of the specific cases are presented in Figs. 3 and 4. In Fig.3 it can be seen that S_{31} and S_{41}, which represent the signal coupled to the second transmission line, increase very slightly over the frequency range of 0 to 60GHz. In Fig.4, it can be seen that there is a much greater variation of the S parameters with frequency. In this case, the amount of coupling is also much greater. From this, it can be seen that results at one frequency do not necessarily imply similar performance at other frequencies. For the statistical characterization, the frequency of 40GHz was chosen. The statistical characterization of the device over a larger frequency range is a matter for future consideration.

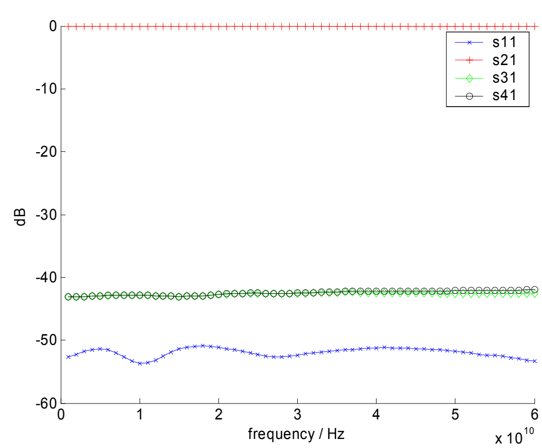

Fig.3 S-parameters for case S=42,W=12,G=84,D=24,H=10, [µm]

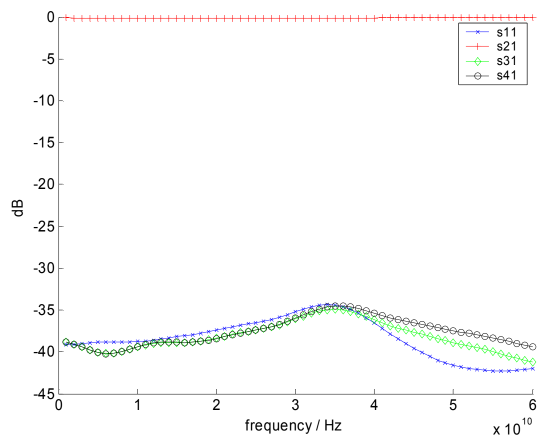

Fig.4 S-parameters for case S=42,W=12,G=252,D=0,H=10 [μm]

Statistical Model Development

From the DOE, first-order prediction models were developed based on only the significant parameters. At the 95% confidence level, the statistically significant parameters were determined to be D, W/S, G/S, and the statistical interaction between D and G/S for the simultaneous prediction of S_{11}, S_{21}, S_{31}, and S_{41}. It was also found that there was an ultimate lack of fit of the first-order models to the S-parameter responses and it appeared to be attributable to curvature in the parameters by inspection of the model validation diagnostics.

For further model development, H was fixed at 20μm because it found not to be a significant parameter. From the RSM, second-order prediction models were developed. Development of the second-order models from the RSM confirmed the results from the DOE that, at the 95% confidence level, the statistically significant parameters were D, W/S, G/S, and the statistical interaction between D and G/S for the simultaneous prediction of S_{11}, S_{21}, S_{31}, and S_{41}. The final RSM models included these statistical significant parameters as well as D^2 to account for the detected curvature. Due to the addition of D^2 in the RSM models the lack of fit was alleviated, as lack of fit could not be confirmed at the 99.9% confidence level. Additionally, the models were validated for assumptions of normality and equal variance of the residuals The final RSM models are given by (1)-(4). By inspection of these equations, each S parameter is seen as a function of D, W/S, G/S, (D)(G/S), and $(D)^2$.

$$S_{11} = 4.642\times10^{-3} - 4.276\times10^{-3}\left(\frac{D-12}{12}\right) + 1.463\times10^{-3}\left(\frac{W/S - 0.6429}{0.3571}\right) - 1.466\times10^{-3}\left(\frac{G/S - 4}{2}\right) + 1.999\times10^{-3}\left(\frac{D-12}{12}\right)\left(\frac{G/S-4}{2}\right) + 2.900\times10^{-3}\left(\frac{D-12}{12}\right)^2 \quad (1)$$

$$S_{21} = 0.9931 + 5.799\times10^{-3}\left(\frac{D-12}{12}\right) - 1.929\times10^{-3}\left(\frac{W/S - 0.6429}{0.3571}\right) - 3.124\times10^{-3}\left(\frac{G/S - 4}{2}\right) - 2.113\times10^{-3}\left(\frac{D-12}{12}\right)\left(\frac{G/S-4}{2}\right) - 3.643\times10^{-3}\left(\frac{D-12}{12}\right)^2 \quad (2)$$

$$S_{31} = 1.249\times10^{-2} - 2.505\times10^{-3}\left(\frac{D-12}{12}\right) + 2.399\times10^{-3}\left(\frac{W/S - 0.6429}{0.3571}\right) - 2.844\times10^{-4}\left(\frac{G/S - 4}{2}\right) + 6.876\times10^{-4}\left(\frac{D-12}{12}\right)\left(\frac{G/S-4}{2}\right) + 3.499\times10^{-5}\left(\frac{D-12}{12}\right)^2 \quad (3)$$

$$S_{41} = 1.052\times10^{-2} - 1.726\times10^{-3}\left(\frac{D-12}{12}\right) + 2.144\times10^{-3}\left(\frac{W/S - 0.6429}{0.3571}\right) + 4.369\times10^{-5}\left(\frac{G/S - 4}{2}\right) + 7.977\times10^{-4}\left(\frac{D-12}{12}\right)\left(\frac{G/S-4}{2}\right) - 2.344\times10^{-4}\left(\frac{D-12}{12}\right)^2 \quad (4)$$

Statistical Model Interpretation and Performance-based Design

The model provides a method to determine the performance of the coupled lines by providing the line parameters. This can be used to predict the performance of a specific configuration, or allow an analysis to be made to determine requirements for line parameters to achieve a required level of performance.

The impedance of the line is largely controlled by W and S. By fixing the W/S parameter in (1)-(4), the S-parameters can be plotted on a surface as a function of the remaining parameters D and G/S. These surfaces can be used to determine the values of D and G/S necessary to meet required values of the S-parameters.

One example how this model can be applied is the determination of the minimum width of ground plane and line separation that are necessary to keep line coupling below a required value. This can often be a very important design consideration. The impedance will most likely have to be a set value to comply with the remainder of the circuit, and this will fix W/S. For the case of W/S=0.285 (S=42, W=12) the S-parameter surfaces are presented in Fig.5. Fig.6 shows the possible values at which G/S and D can be set, represented outside of the crosshatched area, that will fulfill the design constraints of W/S=0.285, S31 < -39dB, and S41 < -40.8dB.

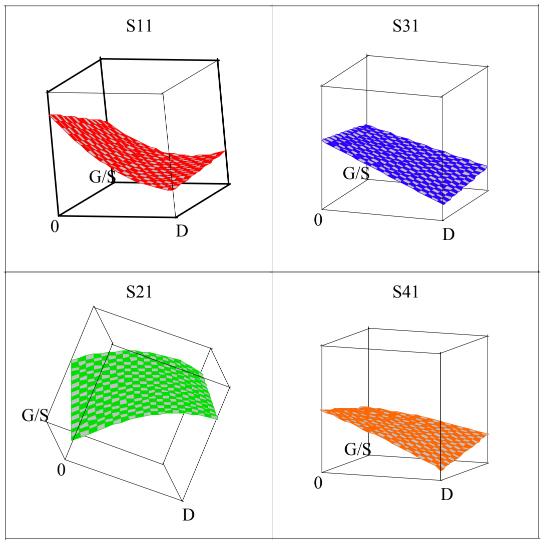

Fig.5 Surfaces representing possible solutions achieved by applying the constraint W/S=0.285

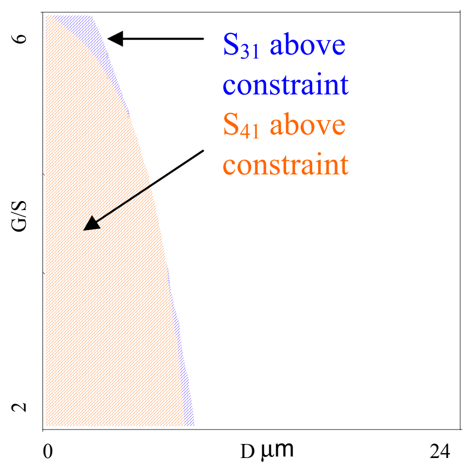

Fig.6 Surfaces representing possible solutions achieved by applying the constraint W/S=0.285

One possible design criterion is to make the lines use the least amount of surface area. Because S and W are fixed for compatibility with the rest of the circuit, the parameters that can be varied are D and G. The ground planes use the largest amount of surface area, and therefore the most compact design will be realized when the ground planes are at their smallest. The case from the above diagram of G/S=2 and D=10 was simulated. Because this case was not explicitly used in development of the statistical model, it can be used to confirm the model. The results of the simulation compared to the RSM 95% confidence intervals defined by the lower and upper bounds for the predicted S-parameters are shown in Table 1.

Table 1 S Parameters from Simulation Compared to RSM S Parameters 95% Confidence Intervals

	S_{11}	S_{21}	S_{31}	S_{41}
Simulation	-45.3389	-0.07786	-38.5531	-40.1279
RSM lower bound	-46.4465	-0.09275	-40.4209	-42.3347
RSM upper bound	-43.3747	-0.07355	-38.2108	-40.1263

Because the S parameters from the simulation occur within the 95% confidence intervals from the RSM, the RSM models were confirmed.

Conclusions

This paper presents a method in which deterministic electromagnetic simulation tools and statistical modeling methods can be used to characterize RF components. In this case, the parasitic coupling between two parallel finite-ground coplanar waveguides has been analyzed. The results of the analysis provide statistical models that can be used to predict performance based on the geometry of the structure. These equations can be used to determine ranges for the line geometrical parameters to produce desired output for a specific design frequency. In effect, the statistical models provide highly efficient, effectively instantaneous results that yield implications of given constraints on the circuit design and performance.

The methods used in this paper can also be applied to other structures. Future work in this area can focus on generalizing the results shown here to cover multiple frequencies, as well as to provide a model for additional line parameters.

Acknowledgments

The authors wish to acknowledge the support of the Georgia Tech NSF Packaging Research Center, The Yamacraw Design Center of the State of Georgia, and NSF CAREER Grant# 9984761.

References

1. G.Ponchak, E.Tentzeris and L.P.B.Katehi, "Coupling Between Adjacent Finite Ground Coplanar Waveguides", *Proc. ISHM 1997 Int. Symp. on Microelectronics*, Philadelphia, PA, pp. 7-10., Oct. 12-16, 1997.
2. K. S. Yee, "Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media", *IEEE Trans. Antennas Propagat.*, vol.AP-14, pp.302-307, Mar. 1966.
3. Box, George E.P. *et al*, Statistics for Experimenters: An Introduction to Design, Data Analysis, and Model Building, John Wiley and Sons, New York, 1978.
4. Neter, John *et al*, Applied Linear Statistical Models, 4th Ed., The McGraw-Hill Companies, Chicago, 1996.