Design and Optimization of 3D Multilayer Balun Architectures Using the Design of Experiments Technique

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I. Introduction

The increased demands for compactness and functionality in modern 3D modules and packages [1] make the design and optimization processes of such systems more and more challenging. Existing optimization packages included in the commercial electromagnetic simulators like High Frequency Structure Simulator (HFSS), often do not take into account the specific effect of each of the factors involved in the design process and the degree of interaction between them, thus leading to time-consuming "trial-and-error" approaches. Alternative optimization methods suited to this kind of complexity are Neural Networks [2] and Genetic Algorithms [3]. These methods are very precise methods, which unfortunately require an extensive amount of prior knowledge and are computationally complex and time consuming. Design of Experiments (DOE) overcomes all these disadvantages. It provides a thorough understanding of all the factors involved in the design process as well as fabrication variations/tolerances, and identifies which ones are more significant, which ones are not significant at all, how they interact with each other, if the goals are achievable in the given conditions, etc. Most importantly, the method is very easy to implement with a negligible computational overhead. As a proof of concept, this paper presents the successful use of DOE in the investigation of a 2.4 GHz multilayer microstrip balun.

II. Balun implementation

For our study, the basic coupled line balun concept presented in [4] has been used. The balun is implemented in 20-layer LTCC with the following characteristics: ε_r = 7.8, tan $\delta = 0.005$, layer thickness = 3.7 mil. In order to save space, the lines have been implemented as spirals. Fig. 1 presents an exploded view of the balun. The optimization of this structure is quite challenging since the close proximity of the turns introduces parasitics and destroys the symmetry of the topology. On the other hand, the conventional optimization would require the variation of a large number of geometrical parameters and a very large number of simulations leading to prohibitive design time.

The design goals are a resonant frequency of 2.4 GHz, as well as excellent amplitude balance and a consistent phase imbalance at the output from 2-3 GHz. Due to the microstrip topology, the structure is not symmetric and the port 3 line is somewhat shortened compared to the port 2 line. This configuration is due to the fact that both outputs are taken from the same level and allowance has to be given for the via that connects the portion of the open line on layer 2 to the rest of the line on layer 1.

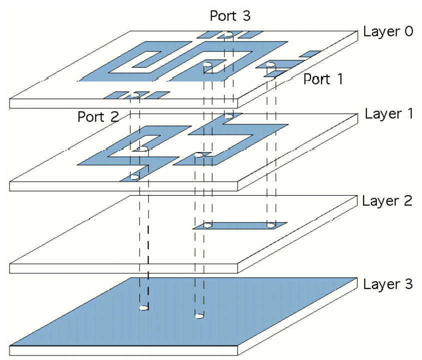

Fig. 1. Implementation of spiral microstrip balun

III. DOE background

A design of experiments is a series of tests in which a set of input variables or factors is purposely changed so that the experimenter can observe and identify the reasons for changes in the output response. Previous work shows the use of design of experiments in modeling of RF/microwave circuits [5]. The factorial designs are used in experiments involving several factors where the goal is the study of the joint effects of the factors on a response. The 2^k factorial design is the simplest one, with k factors at 2 levels each. It provides the smallest number of runs for studying k factors and is widely used in factor screening experiments [6]. This paper shows the first use of DOE in a feasibility study of the optimization of an antenna-related geometry.

IV. Balun optimization

The preliminary simulation of the structure shows poor amplitude balance between ports 2 and 3. A detailed look at the field distribution shows that there is a lot of coupling at the center of the structure. This is due to the fact that the vertical center part of the open line on Layer 0 does not couple with the short lines on Layer 1 and causes coupling with the neighboring lines on the open spiral line. Also, strong coupling is present between the corners of the spiral open on Layer 0 and the two lines connecting the shorts to the ports 2 and 3 on Layer 1. All these coupling effects are illustrated in Fig. 2 on a top view of the structure.

Therefore, two factors have already been identified for the experiment: G_{oo}, or the open-to-open gap, and G_{so}, or the distance the output lines for ports 2 and 3 are moved from the initial position for coupling reduction, as shown in Fig. 5. A third factor L, representing the length by which the lines are shrunk at one end, is added to the experiment for compensating the imbalance between S_{21} and S_{31}. A full factorial experiment with three factors consists of $2^3 = 8$ treatment combinations. The two levels chosen for each input variable have been controlled by the fabrication process. The “-” and “+“ values for the three variables are as follows: 0 and 30 mil for *L*, 0 and 13 mils for G_{so} and 6 and 19 mils for G_{oo}, respectively.

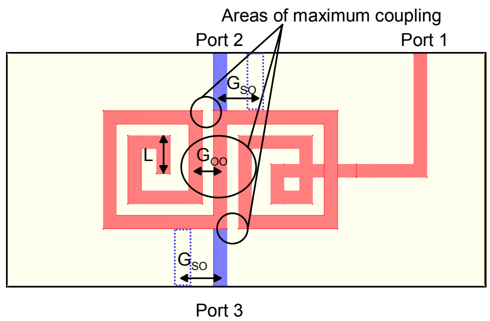

Fig. 2. Top view emphasizing the coupling effects of the balun.

The output variables chosen are Δ_{2GHz} and Δ_{3GHz}, which are the differences between S_{21} and S_{31} at 2GHz and 3GHz respectively, as well as the resonant frequency f_{res}. The optimization goal is: $\Delta_{2GHz} = 0$; $\Delta_{3GHz} = 0$; $f_{res} = 2.4$ GHz. The eight simulations have been run in MicroStripes TLM Modeler. The statistical analysis was performed using JMP statistical software [7]. In this case, the regression models of the outputs representing the imbalance as a function of the inputs are:

$$\Delta_{2GHz} = 1.125 - 0.1625\left(\frac{L-15}{15}\right) - 0.1625\left(\frac{G_{so}-6.5}{6.5}\right) \tag{1}$$

$$\Delta_{3GHz} = 0.75 + 0.125\left(\frac{L-15}{15}\right) \tag{2}$$

These models can be used to predict the performance of the system for a specific configuration or to optimize the balun performance with respect to any one or simultaneous combination of two or all three figures of merit. The initial goal of this optimization was to have $\Delta_{2GHz} = 0$ and $\Delta_{3GHz} = 0$ simultaneously. Since *L* was a significant factor for all three prediction models, G_{so} was fixed at the most convenient levels for achieving the optimal performance (13 mil), and the two derived values needed for *L* to satisfy both $\Delta_{2GHz} = 0$ and $\Delta_{3GHz} = 0$ were $L_{2GHz} =$ 104 mils and $L_{3GHz} =$ -75 mils. These two conditions could not be satisfied at the same time, and this rendered the optimization of the microstrip balun impossible under the described ideal conditions. The two transmission coefficients for ports 2 and 3 could not satisfy the balance requirements in the studied bandwidth (2 - 3 GHz) because the two lines had to be shrunk and elongated at the same time. On the other side, the optimized solution for more relaxed specifications, such as Δ_{2GHz} and Δ_{3GHz} <0.5 dB or <1dB could be easily identified without the need for additional simulations. The $L_{2GHz} = L_{3GHz}$ is calculated from the regression models to be satisfied for a 0.84 dB amplitude imbalance condition. So this particular structure has been optimized as follows: if an amplitude imbalance up to 0.84 dB can be tolerated within the minimum and maximum frequencies, the following are the optimized values for the three variables: $G_{oo} = 6$ mil, $G_{so} = 13$ mil and $L = 26$ mil.

The next step is to perform a weighted optimization for all the three figures of merit Δ_{2GHz}, Δ_{3GHz} and f_{res}. First, the model needs to be checked for ultimate lack of fit [6]. If an ultimate lack of fit is found, curvature in the output response can be investigated. If curvature in the response is detected, Response Surface Modeling (RSM) can account for curvature through second-order model development and the optimization performed based on this new model. Usually, these second-order models are reasonable approximations of the true functional relationship over relatively small regions. Furthermore, more sophisticated optimization methods such as Path of Ascent (POA) can be used. POA determines a path for further optimization of the figures of merit, and is useful especially in cases where the optimal value is not within the initial ranges for the variables. Using this path, another design space is identified and the process repeats with another full factorial DOE. The process is complete when the performance goal or optimum performance is achieved. Results from these advanced DOE-based optimization approaches will be presented at the conference for various 3D LTCC/LCP based antenna structures.

V. Conclusions

The Design of Experiments approach has been combined with full wave EM simulations for studying the feasibility of the optimization of a multilayer balun. It was found that it was not possible to obtain satisfactory amplitude and phase balances for the entire frequency band, but the optimization can be performed if less stringent requirements are imposed on the imbalances. The amount of required simulations was a small fraction (more than an order of magnitude) with respect to any other optimization approaches.

By extending the Design of Experiment (DOE) approach to more sophisticated methods like Response Surface Modeling (RSM) and Path of Ascent (POA), the designer can save a lot of time (order(s) of magnitude), shorten the design cycle of added functions, and achieve the design goals in a simple and elegant manner, while incorporating variations of the fabrication/material processes and eliminating "trial-and-error" deficiencies.

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