Performance Capability Modeling And Optimization Of RF/Millimeter Wave Integrated Functions And Modules Using A Hybrid Statistical/Electromagnetic Technique That Includes Process Variations

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***Abstract* — Various uses of statistical tools combined with deterministic electromagnetic simulators in the analysis, design and optimization of RF and microwave systems are presented. First, the statistical methods are introduced, showing the advantages over the conventional techniques. The statistical tools used in the methodology include sources of variation tools such as ANOVA (Analysis of Variance), SPC (Statistical Process Control), and MC (Monte Carlo) simulation, to account for the process variability. Using this methodology, the developed transfer functions predict both the nominal values and the variation expected for system performance. This is of great value for complex 3D RF integrated modules, RF MEMS and reconfigurable systems, especially at high frequencies where the fabrication tolerances affect the system more due to the smaller circuit features. The methodology can be extended to predict performance of multi-level systems, for which the outputs of the lower-level system become the inputs of the higher-level system. The presented methodology is applied for the analysis, design and optimization of a benchmarking geometry of 60 GHz cavity filters in LTCC (low temperature cofired ceramic) technology.**

***Index Terms* — performance capability, optimization, RF systems, statistical tools, hybrid methods.**

I. Introduction

In recent years, the compactness and functionality required by compact System On Package (SOP) solutions make the design and optimization processes of such systems more and more challenging [1]. For the complicated 3D architectures of RF/microwave multilayer modules, a comprehensive and sophisticated tool is necessary to account for complex phenomena such as coupling and fringing effects. Also, the performance of RF and microwave systems is severely affected by the fabrication process tolerances, especially for the small circuit dimensions at millimeter-wave frequencies. Modeling system performance with transfer functions developed from a methodology based on the integrated use of statistical tools, deterministic simulations, and measurements enable these goals to be achieved [2]. The statistical tools used in the methodology include sources of variation tools such as ANOVA (Analysis of Variance), SPC (Statistical Process Control), and MC (Monte Carlo) simulation combined with DOE (Design of Experiments) tools such as 2^k designs and RSM (Response Surface Methodology) for development of the transfer functions [3, 4]. Using this methodology, the developed transfer functions predict both the nominal values and the variation expected for system performance at the beginning of the design process, thus saving the time and the frustration of the trial and error approach. They provide a thorough understanding of all of the factors involved in the design process, and identify which are more significant, which are not significant at all, how they interact with each other, and if the goals are achievable in the given conditions. The methods are very easy to implement with the use of commercially available electromagnetic and statistical software packages. Additionally, the methods can be easily extended to predict performance of multi-level systems, by separately analyzing each level and then combine them together by using output variables for lower level as inputs for the next level.

II. Benchmarking Structure

The cavity filter considered for the demonstration is built utilizing conducting planes as horizontal walls and via fences as side walls [5]. The size and spacing of via posts are properly chosen to prevent electromagnetic field leakage and achieve stop-band characteristic at the desired resonant frequency. The dimensions of the cavity are chosen to propagate the TE_{101} dominant mode at 60 GHz. Microstrip lines are utilized to excite the resonator through coupling slots etched in the top metal layer of the cavity. The structure is presented in Fig. 1. The four figures of merit chosen to describe system performance are the resonating frequency f_{res}, the insertion loss IL, the return loss RL and the 3dB bandwidth BW. There are three design parameters affected by the LTCC process that are known to affect dramatically these outputs: the slot width w_s, the microstrip feed line width w_f and the cavity width w_c, all shown in Fig. 2. Because the fabrication of the test structures is expensive and time consuming, which is very common especially for 3D architectures, the methodology is based on a combination of electromagnetic simulations and microwave measurements. The first step of the methodology is to statistically quantify both nominal values and variation for the three design parameters that are achievable by current fabrication processes. Next steps include development of the transfer functions that make use of the statistically quantified design parameters to predict the nominal values and process-based variations of the four figures of merit for system performance.

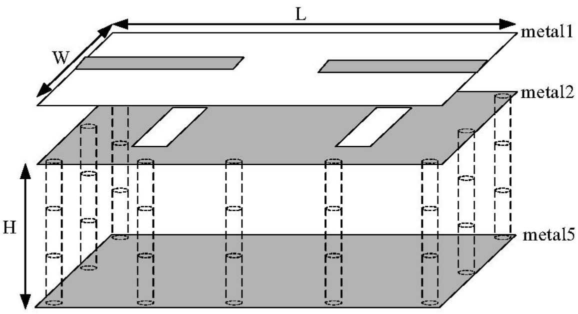

Fig. 1. 3-D overview of LTCC cavity resonator

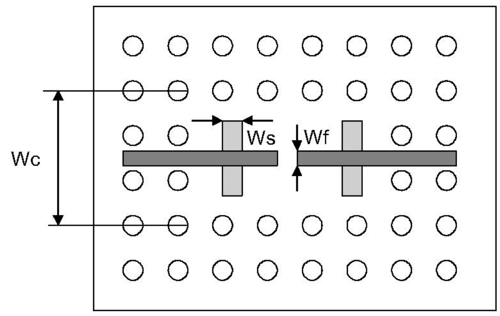

Fig. 2. Top view showing input variables

The transfer functions are developed using Design of Experiments (DOE) and Response Surface Methodology (RSM). The experimentation method chosen for the DOE is a full factorial design with center points [3]. 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. Prior knowledge of the analyzed system is required for choosing the factors and their studied ranges. 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. The design used was a 2^k factorial design with center points. The analysis intervals for the 3 variables are presented in TABLE I.

TABLE I. Ranges for the input variables

	w_c(mm)	w_s (mm)	w_f (mm)
"-" level	1.25	0.11	0.11
"+" level	1.39	0.31	0.2
Center point	1.32	0.21	0.155

The chosen intervals are very wide for the initial analysis presented in this paper, to inspect the general behavior of the system. Future work will reduce these intervals according to the desired goals. Center points in the design increase the capability of investigating the model fit, including curvature in the response, and account for variation in the fabrication process of the structure. Since the statistical models are based on deterministic simulations, the variation of the center points were statistically simulated based on a $\pm 10\,\mu m$ tolerance and a 3σ fabrication process for w_s and w_f, given by the line width and gap tolerance of the process, and a $\pm 1\%$ tolerance and a 3σ fabrication process for w_c, given by the X and Y shrinkage factor for the LTCC substrate. Specifically, 4 additional center points were randomly generated assuming a mean equal to the exact center point value and a standard deviation equal to 3.3333 µm for w_s and w_f, and 4.4 µm for w_c.

III. Statistical Analysis and Optimization

The statistical analysis of the first order models shows which effects and interactions between the factors are significant for each of the four figures of merit and the ones that are not significant are eliminated from the final models. Also, the analysis indicates curvature in the response and the need for second order analysis. In this case curvature has been detected and the second order models, which were investigated for the normality and equal variance assumptions, are presented in (1) – (4).

$$IL = 0.75 - 0.358\left(\frac{w_s - 0.21}{0.1}\right) + 0.206\left(\frac{w_s - 0.21}{0.1}\right)^2 \quad (1)$$

$$f_{res} = 59.879 - 2.357\left(\frac{w_c - 1.32}{0.07}\right) \quad (2)$$

$$\begin{aligned} RL = {} & 25.2 - 0.05\left(\frac{w_c - 1.32}{0.07}\right) + 3.409\left(\frac{w_s - 0.21}{0.1}\right) + \\ & 0.840\left(\frac{w_f - 0.155}{0.045}\right) + 0.526\left(\frac{w_c - 1.32}{0.07}\right)\left(\frac{w_s - 0.21}{0.1}\right) - \\ & 0.402\left(\frac{w_c - 1.32}{0.07}\right)^2 - 1.735\left(\frac{w_s - 0.21}{0.1}\right)^2 \end{aligned} \quad (3)$$

$$BW = 1.448 - 0.064\left(\frac{w_c - 1.32}{0.07}\right) + 0.462\left(\frac{w_s - 0.21}{0.1}\right) + 0.09\left(\frac{w_f - 0.155}{0.045}\right) - 0.019\left(\frac{w_c - 1.32}{0.07}\right)^2 - 0.068\left(\frac{w_s - 0.21}{0.1}\right)^2 - 0.035\left(\frac{w_f - 0.155}{0.045}\right)^2 \quad (4)$$

Before accepting (1) - (4), the models were confirmed. Next, the structure was optimized based on the models for the following goals: 60 GHz resonant frequency, minimum insertion loss, maximum return loss and minimum bandwidth. The optimal was found to be IL = 0.69dB, RL = 25 dB, f_{res} = 59.9 GHz and BW = 1.4 GHz for the following combination of inputs: w_s = 0.23 mm, w_c = 1.32 mm and w_f = 0.11 mm.

Last, the performance capability of the system was evaluated for the optimal structure using Monte Carlo simulation [4]. The Monte Carlo simulation of 1000 trials provided evidence that the given specification limits yield long-term six sigma process capability [6]. TABLE II shows the results of the Monte Carlo simulation.

TABLE II. Predicted performance of the outputs

	IL	RL	f_{res}	BW
Nominal	0.68649	24.96937	59.879	1.412670
USL	0.735	n/a	60.7	1.72
LSL	n/a	21	59.3	n/a
Cp	n/a	n/a	2.08	n/a
Cpk	1.76	1.52	1.71	n/a
Cnpk	n/a	n/a	n/a	1.571348

The first row shows the nominal values of the outputs obtained by plugging in the optimized values of the inputs into the models. USL and LSL are the upper and lower specification limits respectively, and they represent the worst case scenario for each of the outputs. It can be noted that the outputs that have been optimized for a minimum have a USL, the one optimized for maximum has a LSL and f_{res}, which has been optimized for a specific value, has both a USL and a LSL. Cp, Cpk and Cnpk are metrics that quantify the evidence that the system complies with Six Sigma process capability. Six Sigma capability is reached for processes that achieve Cp$\geq$2 and Cpk$\geq$1.5 for processes with USL and LSL, and Cpk or Cnpk $\geq$ 1.5 for processes with only USL or LSL, allowing in both cases the possibility of long-term +/-1.5 sigma shift. In the case of BW, a different metric, Cnpk, was used because the normality assumption was not verified for that output. In this case, TABLE II shows that these conditions were satisfied and evidence that Six Sigma capability that includes the possibility of long-term +/-1.5 sigma shift was reached. In other words, the designer knows at the beginning of the design process that approximately 3.4 measurements out of 1,000,000 may occur beyond these specification limits (i.e., the USL and LSL). If the designer finds these limits unacceptable, the whole system can be redesigned to achieve the desired specification limits, without the need to build any test structures and go through an expensive and time consuming design cycle.

VII. Conclusion

This paper presents a series of methods in which deterministic electromagnetic simulation tools and statistical modeling tools can be combined to model the performance capability and optimize both the electrical parameters of complex RF and microwave systems. First, the system needs to be assessed and the inputs variables and their studied ranges established. Then, the outputs are chosen and the optimization goals determined. The results of the hybrid electromagnetic-statistical analysis generate statistical models that can be used to predict the system performance based on the geometry of the structure. These models can then be used to predict both the nominal values and the variation expected for system performance, as well as optimize the structure with respect to desired performance. They are of great value for complex 3D integrated modules, RF MEMs and reconfigurable systems, especially at millimeter wave frequencies, where the process variability becomes more significant. Also, the methodology can be used to predict the performance of multi-level systems, for which the outputs of the lower-level systems become the inputs of higher-level systems. For this research, the figures of merit, like the insertion loss and bandwidth, will be used as inputs for a front-end module containing the filter together with other passive and active devices. The (1-4) models will be combined with new models describing the entire module for a thorough understanding of the entire multi-level system behavior. In this way, the behavior and challenges of complex RF and microwave systems can be predicted at the beginning of the design process, leading to significant time savings and a much shorter design cycle of added functions, while achieving the design and optimization goals in a simple and elegant manner.

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