Hybrid Statistical/Electromagnetic Optimization and Performance Capability Modeling of an LTCC Compact Soft/Hard Surface Structure

G. DeJean[(1)], D. Staiculescu[(1)], L. Martin[(2)], U. Onyewuchi[(1)], R.L. Li[(1)], M. M. Tentzeris[(1)]

(1) GEDC, School of ECE, Georgia Tech, Atlanta, GA, 30332, U.S.A.

(2) Motorola, Plantation, FL, 33322, U.S.A.

Abstract

A compact softhard surface (SHS) structure is designed to improve the radiation pattern of a patch antenna. The compact SHS structure is realized on a low temperature co-fired ceramic (LTCC) technology. The structure is first optimized using statistical tools such as DOE (Design Of Experiments), then SPC (Statistical Process Control), and MC (Monte Carlo) simulation to account for the performance capability modeling of the system. The method gives the possibility to predict the system performance based on the variability in the geometrical parameters of the structure without the need to build any test structure.

Introduction

As multilayer materials such as LTCC, LCP, and MLO are being utilized for the integration of antennas into SOP modules, there are some concerns that need to be addressed in order to maintain the performance of the antenna [1]. One of the drawbacks of designing antennas on LTCC is the high dielectric constant of the substrate ($\varepsilon_r > 5$), which facilitates the propagation of surface waves, which may be a larger problem at higher frequencies (millimeter-wave range). The most common method of suppressing surface waves is the use of a periodic bandgap structure (PBG) [2]. Sometimes, integrating PBG structures into SOP-based devices may not be suitable for maintaining the compactness of the design because PBG structures can be quite large as a result of the rows of via holes needed to realize the bandgaps. A new implementation using the soft surface properties of a soft-and-hard surface (SHS) structure is applied to a patch antenna on LTCC multilayer substrates [3].

After the preliminary structure is designed, the optimization is performed based on transfer functions developed from a methodology based on the integrated use of statistical tools and deterministic simulations [4]. The statistical tools used in the methodology include sources of variation tools such as ANOVA (Analysis of Variance) combined with DOE (Design of Experiments) for development of the transfer functions [5]. Then, the performance capability of the system is modeled using SPC (Statistical Process Control), and MC (Monte Carlo) simulation [6]. Using this methodology, the developed transfer functions predict in a systematic way both the nominal values and the variation expected for system performance at the beginning of the design process, with no need for building test structures.

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Benchmarking structure

A compact softhard surface (SHS) structure consists of a square ring of shortcircuited metal strips employed to surround a patch antenna for blocking the surface wave propagation, thus alleviating the effect of the edge diffraction and hence improving the radiation pattern. The antenna under optimization consists of one square patch on an LTCC substrate. Around the patch antenna is the proposed SHS, consisting of a number of quarter-wavelength metal strips that are short-circuited to the ground plane. The operating frequency for this SHS is determined by the strip width, not by the thickness of the substrate, allowing for its implementation in arbitrary substrate thicknesses. The operating frequency is 15 GHz, while the size and thickness of the substrate are fixed at 40 mm x 40 mm ($2\lambda_0$ x $2\lambda_0$) and 0.5 mm ($0.025\lambda_0$), respectively. Top and side views of the structure are presented in Figure 1.

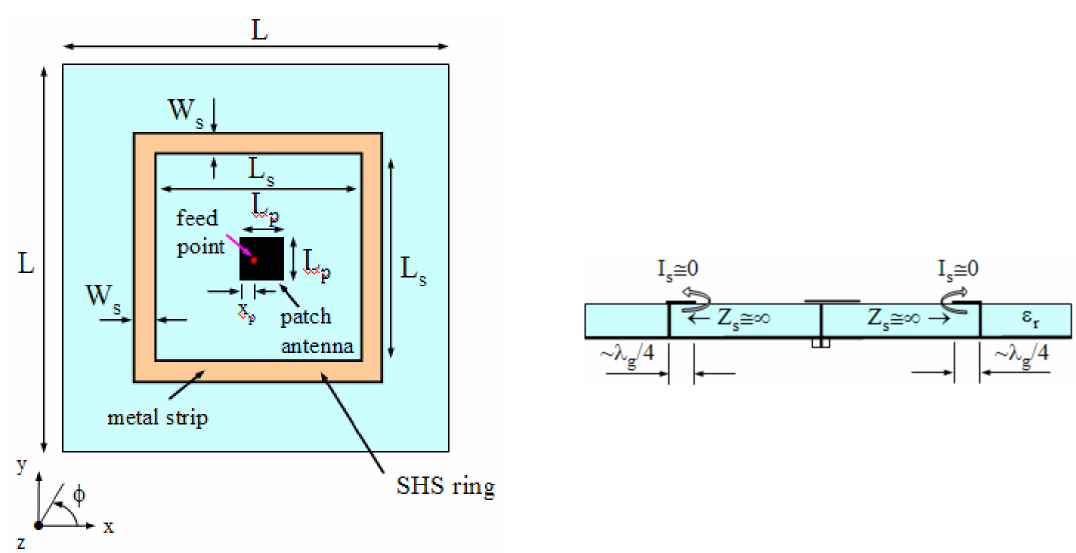

Figure 1. Stacked patch antenna surrounded by SHS structure.

The transfer functions are developed using Design of Experiments. The experimentation method chosen for the DOE is a full factorial design with center points [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 variables that affect this design are chosen to be the length, L_s, and width, W_s, of the soft surface ring. First, a preliminary design of the structure has been simulated. Then, the design space for the two parameters has been chosen such that it represents physically realizable values without severely affecting the performance. The analysis intervals for the two variables are presented in Table 1. The antenna directivity *D*, the front to back ratio *F/B*, and the and the maximum return loss peak *MRLP* between the two resonances are the three responses for the statistical models. They will be optimized as follows: maximize *D* and *F/B* and minimize *MRLP*.

Table 1. Ranges for the input variables

Variable	Min (mm)	Max (mm)	Center Point (mm)
L_s	12	36	24
W_s	0.5	4.5	2.5

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 was statistically simulated based on a ± 10 μm tolerance and a 3σ fabrication process for both inputs, given by the X and Y shrinkage factor for the LTCC substrate.

Statistical optimization and performance capability modeling

The DOE revealed the significant parameters for all figures of merit and then first-order prediction models were developed based on them. At the 95% confidence level, it was found that both inputs are significant for *D* and *F/B* and only L_s is significant for *MRLP*. The assumptions of independence, normality, and equal variance were considered for validation of the statistical models. The first order models developed based upon the DOE data analysis results are given by the (1)-(3).

$$D=6.72-0.29\left(\frac{L_s-24}{12}\right)+0.09\left(\frac{W_s-2.5}{2}\right)-\left(\frac{L_s-24}{12}\right)\left[0.33\left(\frac{W_s-2.5}{2}\right)\right] \quad (1)$$

$$F/B=9.96-0.80\left(\frac{L_s-24}{12}\right)+0.55\left(\frac{W_s-2.5}{2}\right)-\left(\frac{L_s-24}{12}\right)\left[0.85\left(\frac{W_s-2.5}{2}\right)\right] \quad (2)$$

$$MRLP= -9.76-0.59\left(\frac{L_s-24}{12}\right) \quad (3)$$

The optimization is based on the previous models. The goals were maximized directivity and front to back ratio, and minimized maximum return loss peak. The values that satisfied the optimization conditions within the design space of the DOE were L_s = 19 mm and W_s = 4.5 mm, leading to the optimized values of the three figures of merit of *D* = 7.07 dBi, and *F/B* = 11.2 dB and *MRLP* = -9.52 dB.

Last, the performance capability of the system was evaluated for the optimal structure using Monte Carlo simulation [6]. The Monte Carlo simulation of 10,000 trials provided evidence that the given specification limits yield long-term six sigma process capability. Table 2 shows the results of the Monte Carlo simulation. 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 is noted that the outputs that have been optimized for a maximum have a value for LSL, but no value for USL. Cp and Cpk are metrics that quantify 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 $\geq$ 1.5 for processes with only USL or LSL, allowing, in both cases, the possibility of long-term ±1.5 sigma shift. In this case, Table 2 shows that these conditions were satisfied and evidence that six sigma capability, which includes the possibility of long-term ±1.5 sigma shift, was reached. In other words, the designer has knowledge 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 to be unacceptable, the whole system can be redesigned to achieve the desired specification limits without the need of building any test structures; hence, an expensive and time consuming design cycle can be alleviated.

Table 2. Predicted performance of the outputs.

	D	*F/B*	*MRLP*
Nominal	7.07	11.2	-9.52
USL	n/a	n/a	-9.509
LSL	7.054	11.129	n/a
Cp	n/a	n/a	n/a
Cpk	1.56	1.56	1.58

Conclusions

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.

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