Multilayer Embedded Metamaterial Optimization for 3D Integrated Module Applications

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Introduction

The concept of metamaterials, or left-handed (LH), double negative (DNG), negative refractive index (NRI) materials, has been around since the late 1960's [1], but only recently it has gained a lot of interest since practical implementation solutions emerged [2], [3]. These materials exhibit phase and group velocities of opposite signs and a negative refractive index in certain frequency ranges, both characteristics making them desirable for RF and microwave circuits. One of the implementation approaches starts from the equivalent transmission line model and loads a host line with a dual periodical structure of series capacitors and shunt inductors [4]. The length of the period and the value of the capacitors and inductors determine the frequency band in which the material has LH behavior. The goal of this paper is to design and optimize a metamaterial structure for 6 GHz. The current design methods do not take into account the specific effect of each of the factors involved in the design process, the degree these factors interact with each other, and which ones are not statistically significant therefore can be eliminated from further analysis. The presented methodology integrates full wave electromagnetic simulation and statistical tools and is applied for the optimization of a compact 6 GHz metamaterial structure on LTCC (Low Temperature Cofired Ceramic).

Benchmarking structure

The geometry under optimization utilizes a stripline host transmission line implemented on two adjacent layers that is loaded with a distributed series capacitor and a shunt inductor [4]. The capacitor is implemented as an overlapped discontinuity from one layer to the other, while the inductor is a via to the ground plane, as shown in Figure 1. The value of the capacitor and inductor, as well as the length of the entire structure, determine the frequency band in which the material has LH behavior [4].

In order to optimize this structure, the range of the parameter values has to be determined. The three design parameters that affect the metamaterial performance are shown in Figure 1: *p* is the length of the overall structure, *o* is the overlap of the capacitive gap, and *r* is the radius of the inductive via.

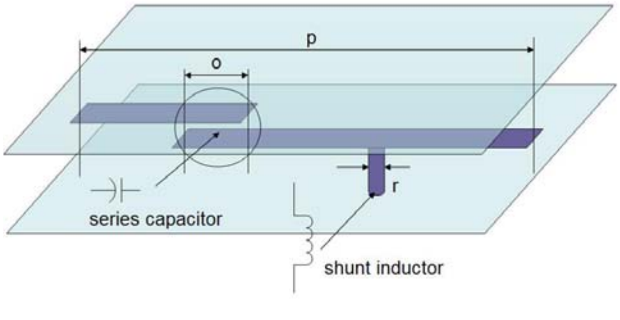

Figure 1. 3D view schematic of the metamaterial structure.

The chosen technology is a hybrid LTCC, including two types of dielectric layers, all 50 μm thick. In this particular case, we used one inner layer, between the two metal layers containing the stripline, to have $\varepsilon_r = 17$, and three layers of a lower dielectric constant, $\varepsilon_r = 7.1$, on each side of the stripline.

First, a preliminary design of the 6 GHz structure has been simulated. Then, the design space for the three parameters has been chosen such that it represents physically realizable values without severely affecting the performance. The ranges for the three input variables are presented in Table 1. The resonant frequency f_{res} and the corresponding insertion loss *IL* are the responses for the statistical models.

Table 1. Ranges for the input variables

Variable	Min (μm)	Max (μm)	Center Point (μm)
p	8200	8800	8500
o	300	400	350
r	65	95	80

The experimentation method chosen for the DOE is a full factorial design. 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 [5].

Statistical model development and optimization

The DOE revealed the significant parameters for both figures of merit and then first-order prediction models were developed based on them. At the 95% confidence level, it was found that all three parameters *p*, *o*, and *r,* as well as the interactions between *p* and *o* and *r* and *o* were statistically significant for the insertion loss and only *o* and *p* were significant for the resonant frequency. 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)-(2).

$$\begin{aligned} IL = 3 &+ 0.095\left(\frac{p-8500}{300}\right) + 0.05\left(\frac{o-350}{50}\right) + 0.262\left(\frac{2r-160}{30}\right) \\ &+ 0.022\left(\frac{p-8500}{300}\right)\left(\frac{o-350}{50}\right) + 0.045\left(\frac{2r-160}{30}\right)\left(\frac{o-350}{50}\right) \end{aligned} \qquad (1)$$

$$f_{res} = 6.15 - 0.216\left(\frac{p-8500}{300}\right) - 0.184\left(\frac{o-350}{50}\right) \qquad (2)$$

The optimization goals were minimized insertion loss *IL* for a target resonant frequency of 6 GHz. Figure 2 shows the surfaces of possible solutions for the optimization goals. The optimization is done based on the intersection of the surfaces, which is also shown in Figure 2. The values that satisfied the optimization conditions within the design space of the DOE were d = 8388 μm, o = 400 μm, and r = 65 μm leading to the optimized values of the two figures of merit of *IL* = 2.7 dB and f_{res} = 6.05

GHz. Figure 2 shows the figures of merit as functions of *o* and *p* with *r* fixed at 65 µm. Figure 3 shows a plot of the simulated optimized metamaterial structure performance.

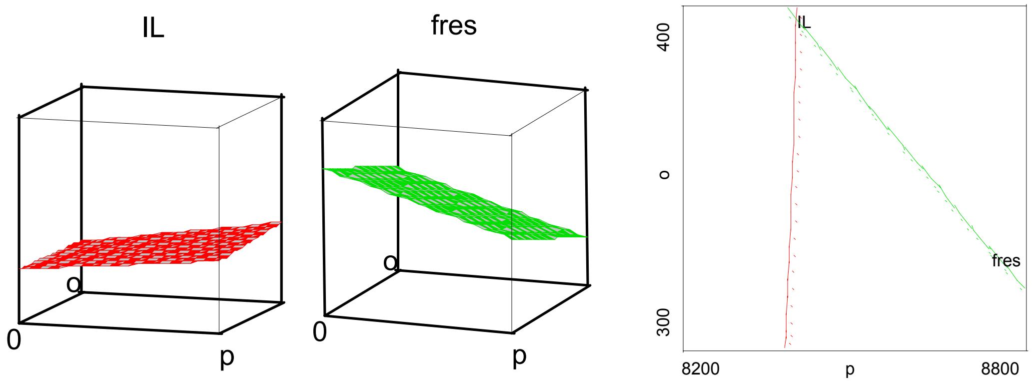

Figure 2. Surfaces representing possible solutions for the optimization goals and intersection of the surfaces representing the optimized condition

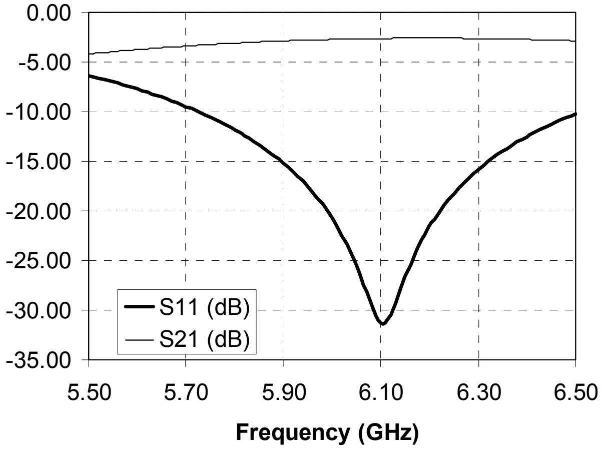

Figure 3. Performance of optimized structure

Next, the effect of the number of cascaded cells has been investigated for the center point. Ideally, such a structure has an infinity of repetitions of the above structure. The higher the number of cells, the more the behavior approaches the ideal case. In this case, the effect of adding one and two more additional cells to the center point case has been studied to understand the behavior of the structure for a small number of repetitions. The result is presented in Figure 4. The increased number of cells degrade the insertion loss in the passband but improves dramatically the rejection in the stopband. Also, there is a shift in resonant frequency and a narrowing of the bandwidth with increased number of cells. These are important considerations to be taken into account at the beginning of the design process.

Conclusions

This paper presents a method in which deterministic electromagnetic simulation tools and statistical modeling methods can be used to optimize RF components and microsystems. A benchmarking geometry of a multilayer metamaterial structure in LTCC technology was optimized. The two optimized responses were the center frequency and the insertion loss. Three geometric parameters of the structure were chosen as experimental factors. The results of the hybrid electromagnetic-statistical analysis generated statistical models that could be used to predict the structure performance based on the geometry of the structure. These models could then be used to optimize the structure with respect to the desired performance, enabling the system-level optimization of the geometry in a quick and inexpensive way. In this case, the center frequency was chosen and the insertion loss was minimized to exemplify the possibilities of the method. Also, the impact of the number of cascaded cells on the system performance has been analyzed.

The proposed approach can be easily extended to a larger number of design variables and optimized figures of merit. In this way, the behavior of a complex system, such as a 3D multilayer module, could be predicted at the beginning of the design process, leading to a much shorter design cycle of added functions, while achieving design optimization goals in a simple and elegant manner.

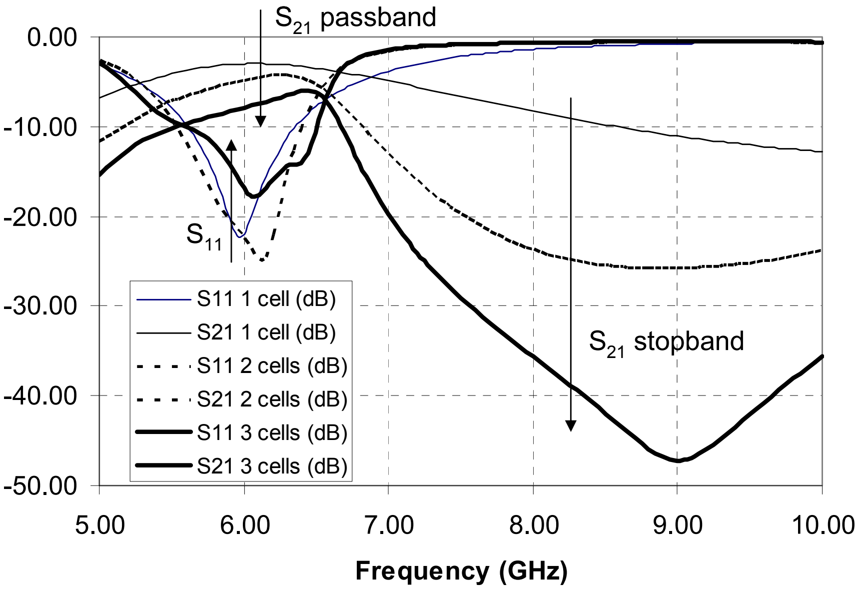

Figure 4. Effect of increasing the number of cascaded cells

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