Design of Metamaterial Textures for Microwave Applications

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1. INTRODUCTION

Recently, in electromagnetics, much has been presented in terms of design [4, 7, 8 and 12]. However, so far all designs have focused on pure shape/metallization design to achieve mostly bandwidth and frequency control. The possibility of material design holds much greater promise for a number of reasons. Only a few off-the shelf materials/substrates exist, i.e. designs are constrained by the limited choice of materials. Certain desirable property combinations are simply unavailable. Since materials have different properties, it seems sensible to make use of the good properties of each simple ingredient by using them in a proper combination allowing for multi-degrees of freedom in design across three dimensions. In addition, the ability to alter material properties subject to certain design specifications is a most desirable feature in electric systems design. There already exist successful material design examples having unusual yet very desirable mechanical [1, 9 and 10], piezoelectric [11] and thermal conductivity [6] properties. Similarly, in electromagnetics more efficient and compact antennas could be created if the material itself could be custom-designed for each application. Nevertheless, although material design can certainly occur in a theoretical environment their commercial availability severely limits the practicality of such designs. In this paper, we propose a way of designing artificial material volumes (or meta-materials) which have pre-specified dielectric constants. We also evaluate the dependency of resulting dielectric constants on the designed texture and material composition. The design method is based on the mix of two or more off the shelf materials (Air and LTCC) to develop a pre-specified dielectric constant ranging from 20-100. A key aspect of the mixing approach is its practicality. That is, once the mixing formula is mathematically developed, we can then proceed with its manufacturing using standard extrusion, solid free-form fabrication or other techniques. It is important to note that the mixing occurs at the micro-scale and therefore the resulting mix is a form of a texture, which is formed by a periodic repetition of a unit cell (Figure 2). This texture is similar to carpet design at a much finer scale.

2. BACKGROUND

In this paper we develop several texture designs and examine their dielectric constants by measuring/calculating the resonance of a simple patch placed on the textures as shown in Figure 1. The employed textures were motivated from a recent study employing material design for negative Poisson's ratio (NPR) and negative thermal expansion coefficient (CTE) [1]. Figure 2 shows an example of a unit cell and the resulting texture, which has NPR properties. This material has the extraordinary feature of expanding transversely when subject to an applied tensile load, which can be used in many applications such as fasteners and shock absorbers. Therefore, they have strong puncture resistance and good toughness.

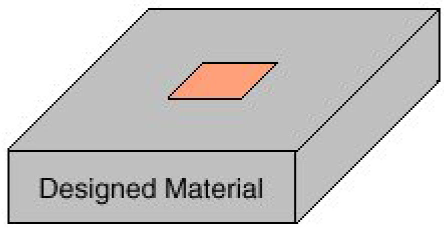

Figure 1: Patch antenna with designed material/texture

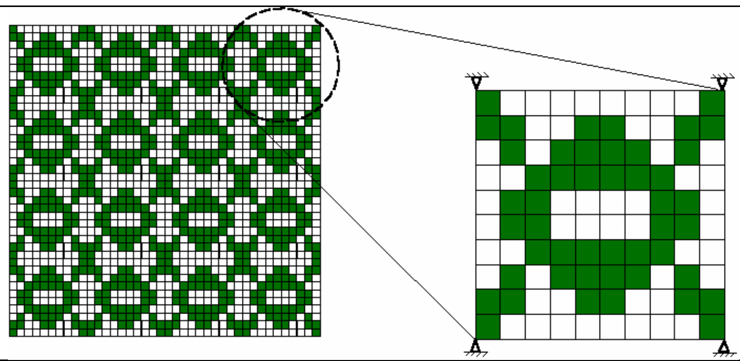

Figure 2: Composite materials of 4x4 array unit cells with negative Poisson's ratio

For our antenna substrate, we consider similar generic unit cells. In our design process, we will turn on/off the material pixels to form the final unit cell. The designed material/texture subject to a pre-specified dielectric constant is proposed to be constructed by a periodic repetition of that unit cell. Each of these textures is characterized by a different material composition on the micro-scale. Consequently, the resulting material surface does not display material variations discernable to human eye. However, the periodicity and the pixel by pixel design approach allows for the practical realization of the designed meta-material which are mixtures of two or more off-the shelf available powders or compositions.

An important aspect of the design process is to evaluate the resulting material textures based on their effective dielectric properties. The ultimate standard goal, as in general composite design, is to establish appropriate micro-mechanical models/formulae to find the effective properties of the designed composite materials. Specific analytical methods in applied mathematics hold exclusively for some specific kinds of composites [1, 2 and 5]. In addition, these complex relations impose geometric and constitutive assumptions. On the other hand, empirical formulae are still the most commonly used approach for the analysis of composites as in the case of the mixture formula and the empirical effective dielectric constant formula [Balanis?] based on the actual resonance of the structure. They are empirical, yet easy and general, and often show good agreement with experimental data. Therefore, these two different approaches are adopted in our study. The aim is to investigate/compare the agreement of dielectric constants predicted by both methods. First, the mixture formula based on the simple arithmetic average of each constituent's volume percentage is used. This method allows for a simple prediction, as the effective property is predicted based on the material percentages of the mixture only and assumes that the designed material is equivalent to a homogenous material. Second, each of the designed textures is evaluated based on the actual resonance of a square patch antenna sitting on it. The actual resonance behavior is simulated through a full wave FE-BI analysis tool for infinite periodic substrates [3]. That is, the effective dielectric constant is predicted taking the actual texture's performance into account. This procedure is adopted for different class of textures with geometrical details explained below.

2.1. Class I Textures

As an example, we proceed to design meta-materials by mixing available LTCC powders of $\varepsilon_r = 100$ with air medium. The basic repetitive unit cell and the resulting texture with the patch sitting on it is shown in Figure 3, where blue portion is LTCC and white portion is air. This unit cell has a size of 250 x 250 μm and a pixel resolution of 25 μm. Variations of the texture are designed by changing the material volume composition. The key idea is that the surface of the dielectric substrate can be considered as a texture, which changes as the mixture of materials is altered. The effective dielectric constants of each designed texture/material are calculated based on two methods explained above. The results are shown graphically in Figure 4 with respect to the material volume composition of each texture. For these small microscopic dimensions, the simple mixture formula seems to predict the behavior of the designed meta-materials very well, as this was to be expected. Furthermore, dielectric constants ranging from 20 to 100 are obtained as a result of mixing two off the shelf isotropic materials.

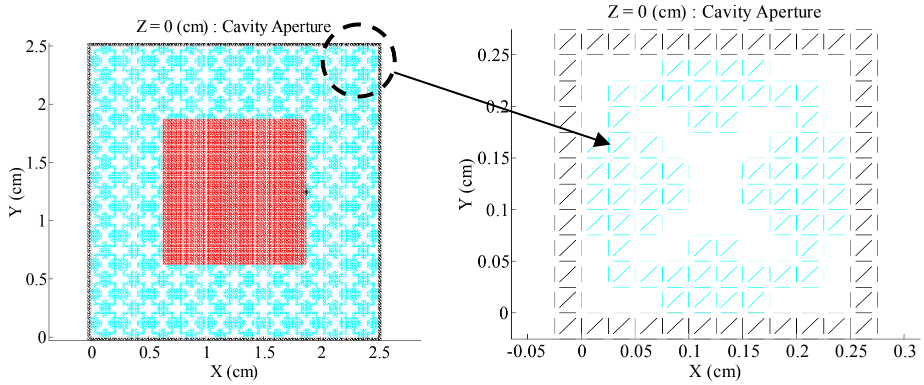

Figure 3: Class I texture sample (left) with basic unit cell (right)

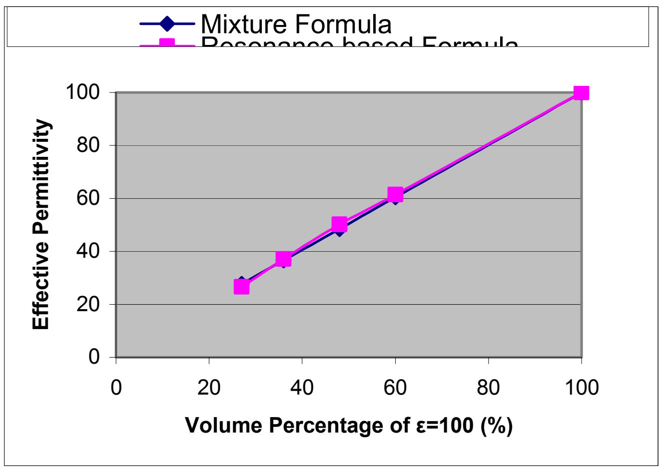

Figure 4: Effective dielectric permittivity wrt. LTCC volume composition for Class I textures

2.2. Class II Textures

To investigate the material composition effect further, a second group of textures is designed. The geometry of the class II textures for the unit cells resemble simple crosses, as is shown in Figure 5. These are easier to manufacture and consequently easier to validate. The dimensions, the constituents and the resolution of the unit cells forming the class II textures are kept the same as the class I textures. Figure 6 shows the predicted effective dielectric constants for the designed textures. As it is evident from this graph, the resonance behavior of the considered textures does not follow the behavior expected by the mixture formula. The dielectric permittivity based on the resonance frequency does not exhibit a linear relationship with respect to the material volume fraction, either. But again, a wide variety of different dielectric permittivities are obtained using only two off the shelf materials. These two results suggest that every texture has its own resolution limit approaching the mixture formula and that the texture supporting the patch has a profound effect on the resulting dielectric permittivity and the resonance behavior of the patch antenna. Consequently, the design capability even for a simple patch antenna is enormously expanded by the mixture of available materials in certain form of textures. The volume percentage of the base materials is not the sole determinant of the effective material behavior.

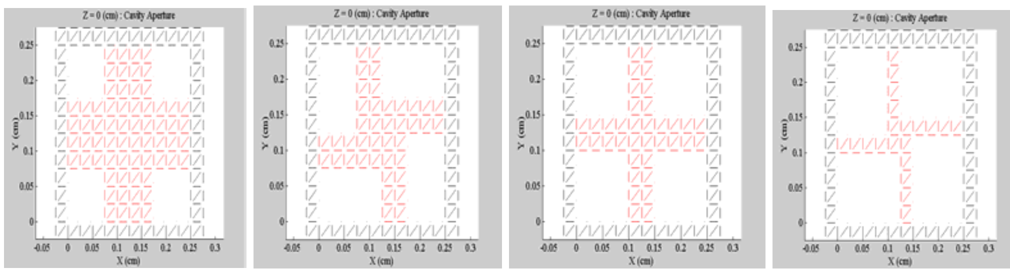

Figure 5 Unit Cell Configurations for Class II textures

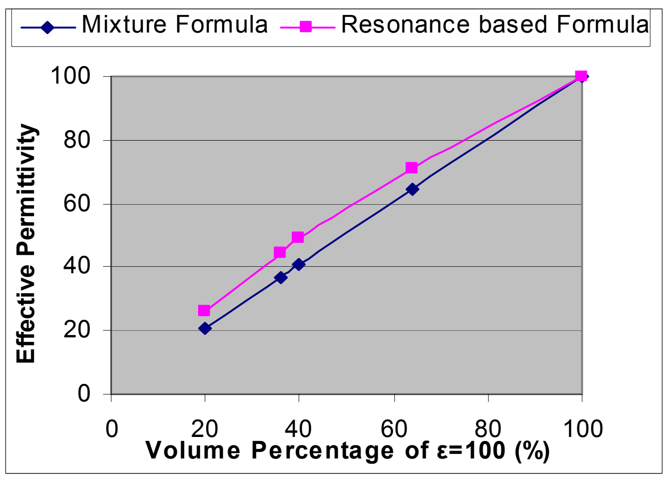

Figure 6: Effective dielectric permittivity wrt. LTCC volume composition for Class I textures

2.3. Class III Textures

In the third group we design unit cells/textures subjected to the same volume fraction of its constituents, namely LTCC and air. The volume fraction of the LTCC powder is kept constant at 64%, a representative value. The designed textures are shown in Figure 7 and their corresponding effective dielectric constants are shown in Table 1 . For the same volumetric compositions, textures attain dielectric constants ranging from 31.25-42.87. From these results we can conclude that artificial materials with different desired dielectric permittivities can be designed by mixing the same amount of material in the form of different textures. Besides, the equivalence of the resulting dielectric constant for different textures (A, B) and the difference of the resulting dielectric constant for the same textures (C, D) suggest the existence of another effect on the synthesized material behavior than volume composition and texture. In fact, designs C and D possess the same texture but their patch location relative to the material texture is different. Additional designs confirmed this behavior: The material textures are frequency agile and their effect on the resulting dielectric constants is strongly coupled to the electric field behavior. The dominant effect on the designed material's dielectric permittivity is the location where the electric fields are high, which for the simple patch is at the boundaries and slightly beneath patch. This is a very important feature to be considered in the automated design of the frequency agile materials.

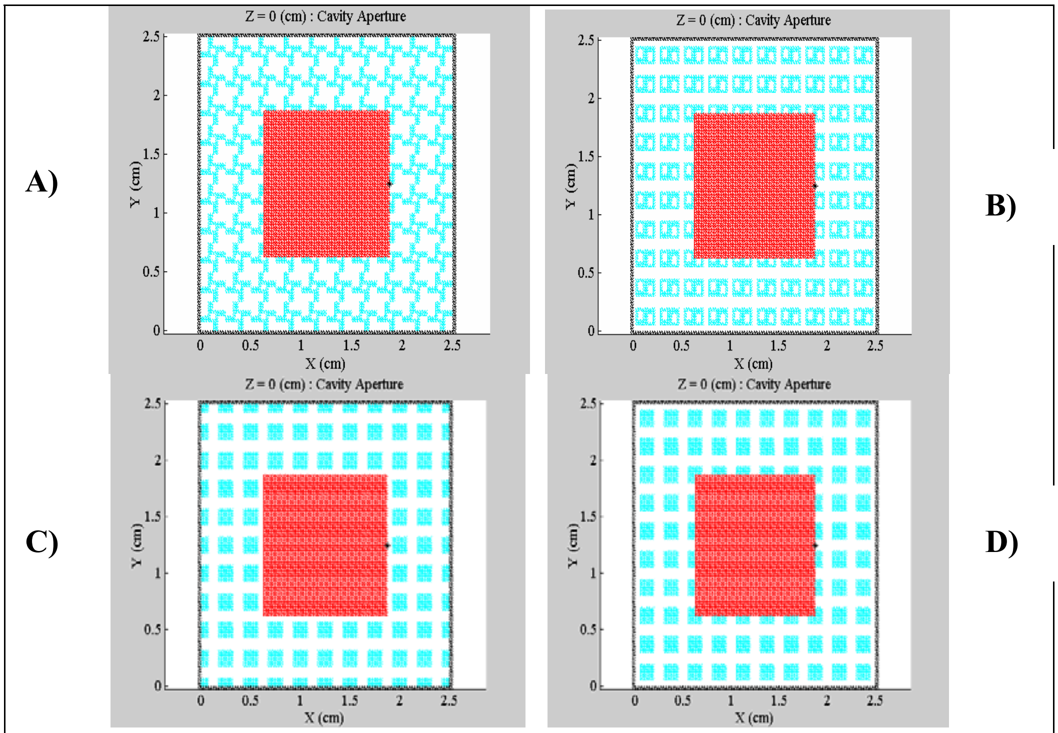

Figure 7 Class III Textures with 64% LTCC

Table 1: Effective dielectric permittivity values for class III textures

Texture	ε_r - Mixture formula	ε_r - Resonance based formula
A	36.64	38.3
B		38.3
C		31.25
D		42.87

3. CONCLUSION

In this paper we demonstrated the design capability of delivering artificial or synthesized meta-materials, which have pre-specified dielectric constants ranging from 20-100. Such a design capability was achieved using available off the shelf materials, namely LTCC powder and air medium. Some of the designs will be manufactured and tested using Solid Free Form fabrication technique and further designs using more than two base materials will be presented in the conference. Furthermore, we have demonstrated that for some material textures the simple mixture formula does not hold and needs to be revised based on the material composition. In addition, material textures are shown to be frequency agile, as the resulting dielectric permittivities showed high dependency on the material detail near the boundaries of the patch. These results suggest the possibility to design materials subject to important design criteria such as bandwidth, efficiency and isolation improvement using more rigorous methods.

4. REFERENCES

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