Effective Medium Properties of Finely Periodic Substrates

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***Abstract* — This work aims to create high-Q bandgap resonators and filters by making fine periodic structures inside an otherwise homogeneous material. The result is to create local control of the dielectric constant and loss tangent. The analytical evaluation of the effective medium is done by both quasi-static and full wave simulations. The focus of the analysis was mainly on three types of periodicities, the so called window pane periodicity, the stratified periodicity, and the cross-hatched periodic media. It is found that the type of small scale periodicity controls the effective dielectric constant to a great extent, with a stratified media reducing the dielectric constant significantly more for a given amount of substrate removal than the window pane periodicity. Accurate characterization was achieved to within 0.5 % between the different analysis methods. Low-loss materials with loss properties that are better than that found in nature are determined, and therefore is a form of metamaterial in itself. In addition the local control of the dielectric constant is an enabling step in creating bandgap metamaterials from a single constituent substrate.**

1. Introduction

The focus of this investigation is the use of fine scale periodic patterns in a material to give local control of the dielectric constant (shown in Fig. 1). Small scale perforations locally reduce the dielectric constant and loss with the elimination of neither dimensional tolerances of the ceramic nor the structural support of the material. This fine scale periodic material is for use in low-loss cavity filters embedded in a substrate not suitable for high-Q filtering [1]. This effort is focused on reducing the factor that limits the performance of distributed components embedded inside an LTCC package, mainly the relatively high loss of the substrate [2]. However, this concept is general enough to be applied to many materials. The loss tangent is the limiting factor in the insertion loss performance of the narrowband filters that we are trying to create, and therefore a decrease in the loss tangent through material manipulation will give us significantly better performance. By changing the percentage of material removal, we can manipulate the effective dielectric constant of the effective medium to any desired amount. Thus, we can synthesize the effective dielectric constant required by an optimal design which may be impossible from natural materials. New material properties can therefore be created from naturally occurring materials which is useful in many bandgap applications which require varying dielectric constants.

2. Analysis Techniques

Analytical and numerical simulations have been run to determine what the effective dielectric constant is for materials with different types of periodic removal. There were three techniques utilized in order to give different types of verifications for different measures of the material performance. The end results of the analysis are graphs of the effective dielectric constant and the loss tangent of the material versus the removal percentage of the substrate, which will be further used as design criteria for filter development

A. Quasi-static Method

The effective dielectric constant can be determined through a quasi-static analysis. This analysis, though approximate, was assumed to be reasonably accurate for periodicities on a fine scale (less than one tenth of wavelength) and was verified using full wave techniques. Since these materials are to be used in a reduced height parallel plate, the polarization of interest is known and the electric field will be perpendicular to the parallel plate. We are not currently worried about anisotropies of the material, though these could be utilized for further filter designs. [3]

B. Full-Wave Cavity Method

The simulation of a metallic cavity with the periodic material embedded inside was performed by a commercial full wave FEM code, Ansoft HFSS®. The effective dielectric constant can be found simply by matching the resonant frequency of the cavity to that expected from an equivalent effective homogeneous material. The loss tangent can be derived by the quality factor calculated from full-wave cavity method by de-embedding the metallic loss or by running simulations with PEC boundaries.

C. Full-Wave Single Cell

An eigenvalue solution is performed with a periodic boundary applied across a unit cell with an applied phase shift. The phase shift is extrapolated to be an equivalent propagation vector and the eigen frequency is used to determine the phase velocity using the equation $v_p = \omega/\beta$. It is interesting to note that the loss tangent is accurately described by the inverse of the unloaded Q of this eigenvalue simulation as well, even though a full cavity is not simulated.

D. Results

It is shown in figure 2 (left) that the quasi-static solution gives an effective medium only .05% different than the full wave solutions. Larger variations are seen for periodicities on a courser scale (> $\lambda/10$). In figure 2 (right) it is shown that the difference between full-wave single cell solution and cavity method is within 0.5% for both the loss tangent and the dielectric constant. The correspondence is exact to within 0.5 % for all three methods for a periodicity which is less than $\lambda/15$. For very fine periodicities full-wave cavity simulations can take up to 4 hours or more on a 2GHz Pentium 4 PC with 1 GB memory. However full-wave single cell simulations take mere seconds, extremely faster than the relatively expensive cavity simulation. Therefore methods such as the extrapolation of dielectric parameters from a single cell are needed to avoid the brute force approach for more complex simulations such as a full filter design. Representing the media as an effective dielectric constant is a method to bridge the length scale problem and to enable the simulation of large scale problems (such as the filter) while still capturing the effect of the small scale periodicity.

3. Analysis of Basic Periodicities

The effect of changing the dielectric constant and decreasing loss tangent greatly depends on the type of periodicity chosen. Since the size of the pattern is small compared with wavelength, quasi-static solutions are sufficient to analyze the field locally. From this local dielectric constant determination, the bulk properties of the material can be derived. For a window pane periodicity, the derived quasi-static solution shows

$$\varepsilon_{EFF}(\text{window pane}) = F+\boldsymbol{\varepsilon}_r(1-F) \tag{1}$$

$$Q_{DIEL} = F/((1-F)\varepsilon'_r \cdot loss\_\tan) + 1/loss\_\tan \tag{2}$$

where F = Area of air inclusion/Area of Period. For example, in Ferro® A6, an LTCC with manufacturer specified dielectric constant of 5.9 and a loss tangent of 2e-3 [4], the periodic removal with 10 mil air gaps in an 11 mil period gives an effective dielectric constant of 1.85 with a corresponding Q_{diel} of 902. This corresponds to a loss tangent of 1.11e-3.

For a stratified dielectric (shown in figure 4), the quasi-static solution is

$$\varepsilon_{EFF}(\text{stratified}) = \boldsymbol{\varepsilon}_r/(\boldsymbol{\varepsilon}_r*F+(1-F)) \tag{3}$$

$$Q_{DIEL} = \varepsilon'_r \cdot F/((1-F)*loss\_\tan) + 1/loss\_\tan \tag{4}$$

where F = Thickness of air/Thickness of the period. In the same LTCC material, the same effective dielectric constant material as the example in the window pane periodicity would have a Q_{diel} of 2884, corresponding to a loss tangent of 3.47e-4.

As seen by a comparison of Fig. 3 and 4, the spatial arrangement of the material and the choice of periodicity have a dominant effect on the loss tangent of the effective medium. In the window pane case, the dielectric constant decreases linearly with the percentage of material removal. However its loss tangent does not improve significantly until a very large percentage of removal. While in the stratified case, a small percentage of material removal can cause a significant change in the dielectric constant and loss tangent. This phenomenon can be easily understood intuitively: the boundary condition at the edge of the dielectric enforces fields to be stored much more in air region of the stratified case than that of the window pane case. Thus, the dielectric constant and loss tangent changes are more obvious in stratified case with a much less significant reduction in the amount of material. We can utilize the stratified structure to manipulate dielectric constant and loss tangent by just removing a small portion of material which is easier to realize. The steep slope of this material can be helpful or a hindrance, depending on the application. We should avoid the sensitive region when the removal percentage is small for filter applications, however this effect may be utilized in certain sensing or tunable applications.

Though stratified periodicity gives a larger control on dielectric constant and a lower loss tangent, it may be hard to realize except for locally within a substrate due to mechanical issues. Thus, cross hatched periodicities was analyzed as well. Layer by layer the period of the window pane was shifted by a half period such that the veins of the window panes do not lie on top of each other. Results for this pattern are somewhat between the stratified and the windowpane for the same effective dielectric constant, which is intuitively satisfying since it is a hybrid between the two cases. The resulting loss tangent for an effective dielectric constant of 1.85 would have a loss tangent of 8e-4 (Q_{DIEL} = 1250).

4. Implications towards Other Materials - Synthesized Alumina from Periodic Titania

To illustrate the strength of this concept, an example of synthesizing alumina (ε=9.8, loss tan=2e-4) by removing some portion of titania (ε=100 and loss tan of 4e-4) is given. In Fig. 5 only 8 % of the dielectric would need to be removed and the effective loss tangent would be 3.7e-5. If this was performed using the window pane periodicity, 90 % of the material would have to be removed and the loss tangent would be 3.64e-4. From this comparison it is very clear that the stratified structure gives a significantly better performance than does the window pane structure in terms of the loss tangent for an equivalent effective medium. The high dielectric constant of the material exaggerates the effect of the periodicity on the loss tangent and therefore highlights the importance in utilizing the correct small scale pattern.

5. Conclusions

A method of creating an effective dielectric constant by patterning a material on a small scale was shown. Three analytical techniques show consistent computation results. Quasi-static and full wave single cell methods are fast and accurate when the unit cell inside the material is small compared to wavelength. Analysis shows the stratified periodicities has a superior performance in terms of loss improvement and dielectric constant tuning. Synthesized alumina created out of titania is shown to theoretically have a much lower loss tangent than natural alumina. The local control of the dielectric constant is useful for both reducing the loss of previously created bandgap filters and in forming novel bandgap structures out of a single host material.

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References

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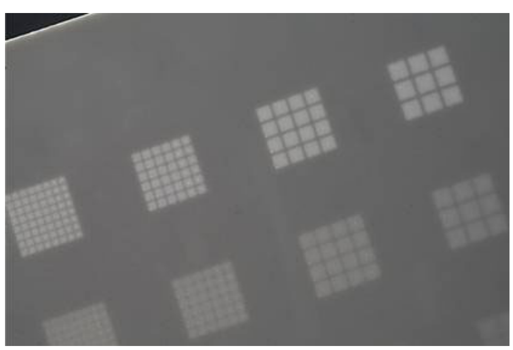

Fig. 1 LTCC Test Vehicle to Show Different Period Ratios and the Percentage of Material

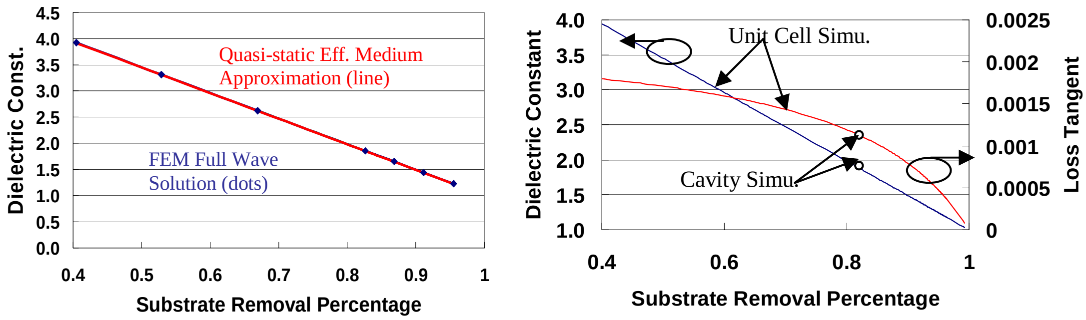

Fig. 2 Left: Verification of the quasi-static solution vs. a full wave simulation. Right: Verification of the single cell simulation (time < 10 seconds) vs. a full cavity simulation (simulation time 30 minutes).

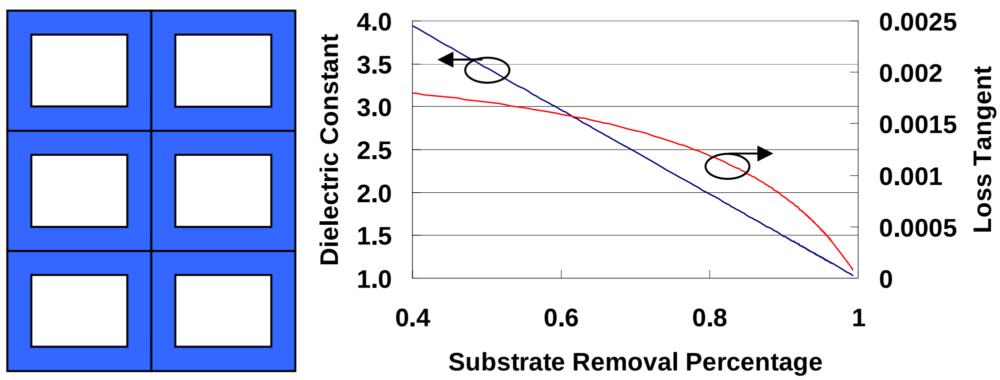

Fig. 3 Window Pane Periodicity and Its Dielectric Property Change vs. Percentage of Material Removal.

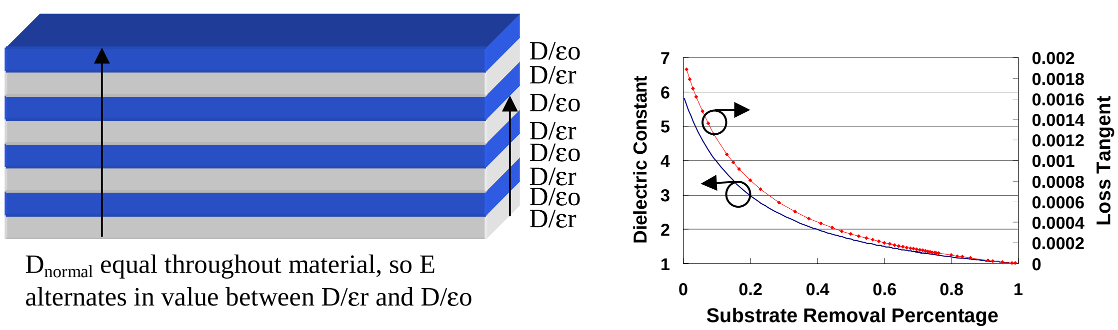

Fig. 4 Stratified Periodicity and Its Dielectric Property Change vs. Percentage of Material Removal.

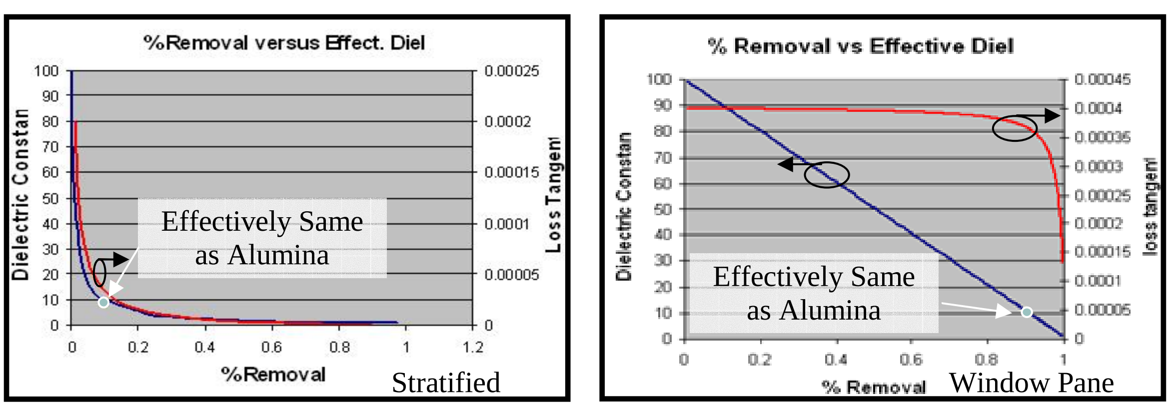

Fig. 5 Comparison Between Stratified and Window Pane Structure in Synthesizing Alumina by Titania