An Efficient PEEC Algorithm for Modeling of LTCC RF Circuits With Finite Metal Strip Thickness

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***Abstract*—In this letter, a simple but effective method is introduced to facilitate the partial element equivalent circuit (PEEC) algorithm to model multilayered low-temperature co-fired ceramics (LTCC) embedded RF circuits with finite metal thickness. The method makes use of the quasistatic assumption that charges only reside on the surfaces of a conductor. In the calculation of the coefficient of potential matrix, one thick conductor plate is treated as two inter-connected zero-thickness plates. Recombining the two plates analytically can correctly account for the increase of plate-to-plate capacitance without adding extra elements to the resultant equivalent circuit model. Experimental results have verified the validation of the proposed method.**

I. Introduction

TO PROVIDE low conductor loss, the thickness of the metal strips in low-temperature co-fired ceramics (LTCC) circuit is fairly noticeable as compared to the minimum thickness of a tape layer. For example, the nominal thickness of buried conductor in LTCC ranges from 10 to 20 μm, whereas the typical thickness of a layer of LTCC type is about 43 to 90 μm. The ratio of metallization thickness to the thinnest thickness of LTCC substrate is nearly 1 to 3! Obviously, the metal thickness in such an integrated passive circuit cannot be ignored and must be taken into account in computer simulation at design stage.

With the increase of popularity of the LTCC technology, it has been of interest to develop a fast and effective algorithm for designing and modeling of passive devices embedded in a homogeneous substrate. Among various algorithms, the quasistatic partial element equivalent circuit (PEEC) algorithm [1] is found particularly suitable to modeling such LTCC devices due to their small electrical size. Recently, it has been successfully applied to the characterization of multilayered LTCC devices [2] with the assumption of infinitely thin metal strips. In this letter, in contrast, we will focus on using the PEEC algorithm to model multilayered LTCC structures in which the thickness of the metal strips is of a major concern. At the same time, the proposed method is also used to compensate the edge effect in the inductance calculation. Experimental results have verified the validation of the proposed method.

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II. Theory

A. Basic PEEC Model

If basis functions are piecewise constant and the quasistatic condition are assumed, three major equations for constructing the equivalent network model of a multilayered structure can be obtained using the formulation described in [1]

$$R_m = \frac{l_m}{\sigma_s w_m} \tag{1}$$

$$\frac{4\pi}{\mu} \cdot Lp_{mn} = \frac{1}{w_m w_n} \iint G_A(\mathbf{r}, \mathbf{r}')\, ds ds' \tag{2}$$

$$4\pi\varepsilon \cdot ps_{ij} = \frac{1}{s_i s_j} \iint G_\phi(\mathbf{r}, \mathbf{r}')\, ds ds' \tag{3}$$

where σ_s is the surface conductivity, and R, Lp and ps are analogous to resistance, inductance and coefficient of potential of the resulting equivalent circuit model respectively.

Fig. 1(a) shows a group of typical meshes used in the PEEC, in which the capacitive meshes are represented by dashed line and the inductive meshes are represented by solid line. As seen in the figure, each capacitive mesh is associated with a network node in the corresponding equivalent circuit. Once the meshes are generated and the nodes are identified, (2) and (3) can be applied on each pair of inductive and capacitive meshes, respectively, to calculate their partial mutual inductance and coupling capacitance. For simplicity reason, only the self- inductance and capacitance are shown in Fig. 1(b).

B. PEEC Model With Finite Metal Thickness

In practical LTCC RF circuits, the layer-to-layer dielectric thickness can be very thin as compared to the metal strip thickness. When this is the case, the zero-thickness approximation cannot correctly model the structure and a modification of the algorithm will be required. One trivial solution to the problem is to use the rigorous three-dimensional PEEC formulation. However, this method will undesirably increase the number of components in the resultant equivalent circuit and significantly increase the computation time in circuit simulation.

To overcome this finite thickness problem without increasing the number of components, a simple modification to the zero-thickness model is proposed in this letter. First of all, we should treat a thick conductor plate as a bar with finite thickness during the partial inductance calculation. Secondly, it is clear that a thick metal strip has at least two surfaces – the top and bottom surfaces (the side conducting surfaces can be treated in exactly

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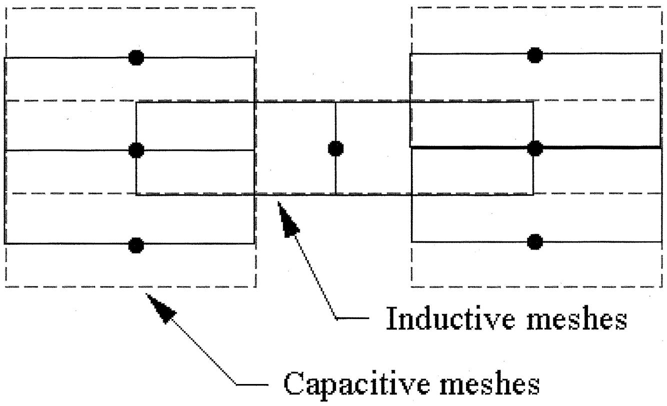
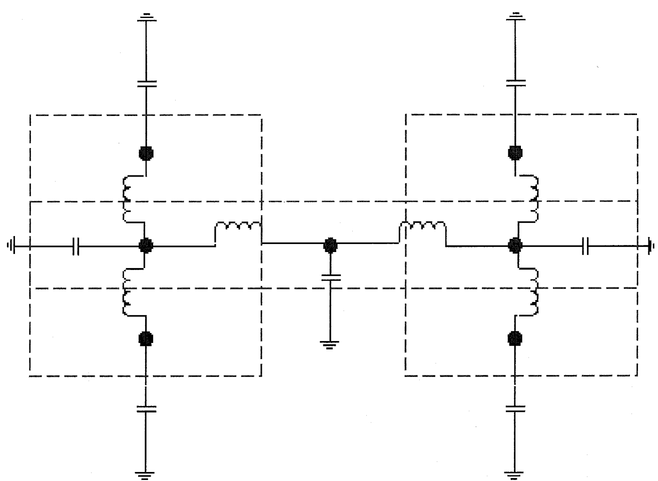


(a)



(b)

Fig. 1. (a) Typical PEEC meshes. (b) The associated equivalent circuit.

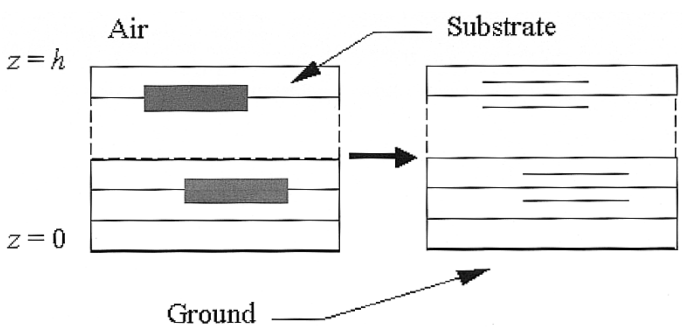


Fig. 2. Replacing a thick metal plate with a pair of zero-thickness ones.

the same way but are ignored in this study) for the charges to reside. If we consider only the top and the bottom surfaces, two infinite thin plates can then be used to replace one thick metal plate. Fig. 2 presents this concept in a graphical manner. In fact, this replacement will turn a thick metal multilayered structure into a zero-thickness counterpart with the number of plates doubled.

After the replacement, the standard zero-thickness PEEC algorithm can then be applied to the structure and the corresponding coefficient of potential matrix will look like

$$\begin{pmatrix} \varphi_{top} \\ \varphi_{btm} \end{pmatrix} = \begin{pmatrix} \mathbf{PS}_{top,top} & \mathbf{PS}_{top,btm} \\ \mathbf{PS}_{btm,top} & \mathbf{PS}_{btm,btm} \end{pmatrix} \begin{pmatrix} \mathbf{Q}_{top} \\ \mathbf{Q}_{btm} \end{pmatrix}. \quad (4)$$

Notice that the coefficient of potential matrix has size of $2N \times 2N$ since we have twice the number of plates. In order to keep the same number of circuit components as that of zero-thickness model, we need to reduce the size of the matrix to $N \times N$. It can be done by first rewriting (4) as

$$\begin{pmatrix} \varphi_{top} \\ \varphi_{btm} \end{pmatrix} = \begin{pmatrix} \mathbf{PS}_{top,top} & \mathbf{PS}_{top,btm} - \mathbf{PS}_{top,top} \\ \mathbf{PS}_{btm,top} & \mathbf{PS}_{btm,btm} - \mathbf{PS}_{btm,top} \end{pmatrix} \times \begin{pmatrix} \mathbf{Q}_{top} + \mathbf{Q}_{btm} \\ \mathbf{Q}_{btm} \end{pmatrix} \quad (5)$$

and then subtracting the first row from the second row, that is (see (6) at the bottom of the page).

Here, we have enforced the condition of $\phi_{top} = \phi_{btm}$ because the top and bottom surfaces are electrically connected. Finally, using the second row, $\mathbf{Q}_{btm}$ can be written in terms of $\mathbf{Q}_{top} + \mathbf{Q}_{btm}$, which leads to

$$\varphi_{top} = \mathbf{PS}_{\text{eq}} \left(\mathbf{Q}_{top} + \mathbf{Q}_{btm} \right). \quad (7)$$

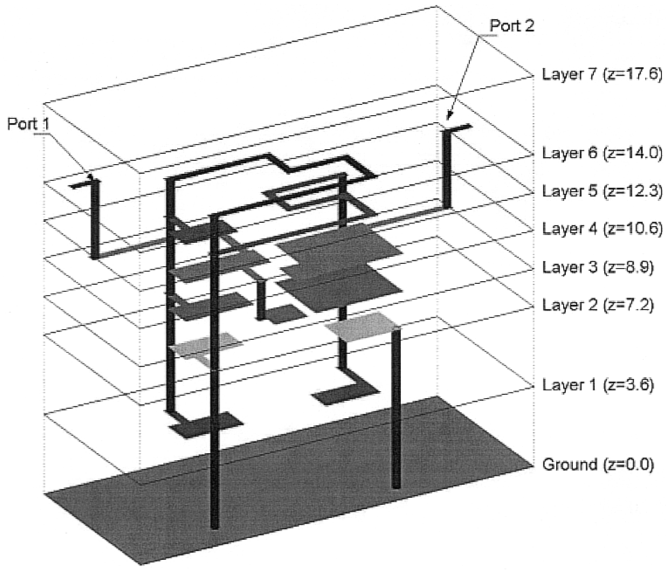
The $N \times N$ matrix, $\mathbf{PS}_{\text{eq}}$, is the reduced coefficient of potential matrix and will be used in the PEEC algorithm to construct the equivalent circuit.

III. Numerical and Experimental Results

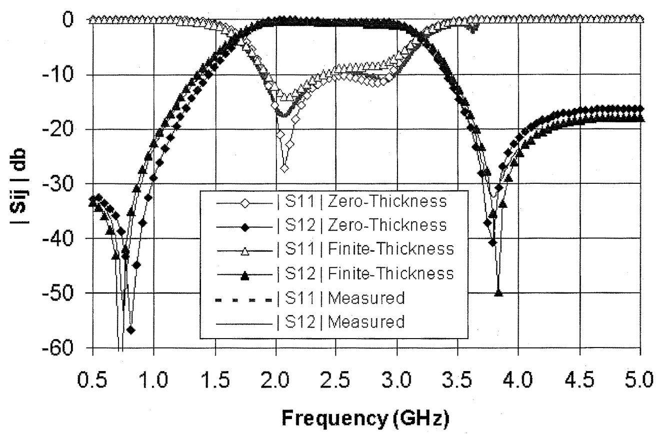
An LTCC band-pass filter used for a GSM/DCS diplexer design have been built and tested to verify the proposed model. The filter was built using the tapes with dielectric constant of 7.8 and the thinnest thickness is 43.2 μm . The buried conductor ink is with nominal thickness of 12 μm and conductivity of approximately 4.9 $\times 10^7$ Siemens per meter. In other words, the thickness of the metal strips is about one third of that of the thinnest tape. The capability to accommodate the finite thickness of the metal strips is crucial for this type of designs.

Fig. 3(a) shows the physical layout of the bandpass filter. As shown in Fig. 3(b), the zero-thickness model underestimates the capacitance values. As a result, the bandwidth of the filter tends to be narrower than that in the reality. By using the finite-thickness model, the effective thickness of the parallel-plate capacitors in computation is decreased and consequently the capacitance increases. The measured results in Fig. 3(b) have verified the effectiveness and validation of the proposed model. It is worth to mention that the PEEC model is about 100 times faster than the commercially available full wave planar circuit EM solvers in simulating the circuits of this kind.

$$\begin{pmatrix} \varphi_{top} \\ 0 \end{pmatrix} = \begin{pmatrix} \mathbf{PS}_{top,top} & \mathbf{PS}_{top,btm} - \mathbf{PS}_{top,top} \\ \mathbf{PS}_{btm,top} - \mathbf{PS}_{top,top} & \mathbf{PS}_{btm,btm} - \mathbf{PS}_{btm,top} - \mathbf{PS}_{top,btm} + \mathbf{PS}_{top,top} \end{pmatrix} \begin{pmatrix} \mathbf{Q}_{top} + \mathbf{Q}_{btm} \\ \mathbf{Q}_{btm} \end{pmatrix} \quad (6)$$



(a)



(b)

Fig. 3. (a) Layout of an LTCC bandpass filter. (b) The comparison of the measurement and PEEC simulation results with zero-thickness model and finite-thickness model.

IV. Conclusions

It has been found that when the thickness of the metal plates is comparable to that of the dielectric layers, conventional PEEC model with zero-thickness metal plate approximation would fail to model many practical structures. In fact, the plate-to-plate capacitance is, in general, higher than those predicted by the zero-thickness PEEC model without compensation. As discussed in this letter, the compensation in the plate-to-plate capacitance can be accomplished by replacing one thick metal plate with two connected infinite thin metal plates in the calculation of the coefficient of potential matrix. Experiment results have confirmed the validation of the proposed model. The proposed simple but effective PEEC model would be very useful for those LTCC RF circuit designs, where the computational speed and capability of handling finite thickness of metal plates are of major concerns.

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