An Explicit Knowledge-Embedded Space Mapping Technique and Its Application to Optimization of LTCC RF Passive Circuits

Ke-Li Wu, *Senior Member, IEEE*, Rui Zhang, Michael Ehlert, and Da-Gang Fang, *Fellow, IEEE*

***Abstract*—A novel explicit knowledge embedded space mapping (SM) optimization technique is presented in this paper. It generalizes the implementation procedure of the efficient SM technique by introducing a buffer space called embedded knowledge space between the original coarse model space and the fine model space, where the ingredients of the coarse model space can be completely different from those of the fine model space. Therefore, this generic scheme can be used to map the coarse model space of arbitrary physical content to the fine model space of different physical content through the embedded knowledge space that is built up with the available radio frequency (RF) circuit CAD formula. The emphasis of the application of the proposed scheme is put on the design of low temperature cofired ceramic (LTCC) RF passive circuits in this paper, along with the required CAD formulas (knowledge) for typical embedded multilayer passives. The effectiveness of the proposed new scheme is demonstrated through two design examples of LTCC lumped element band pass filters for wireless applications. The detailed procedure and flowchart of the proposed implementation scheme are also given in the paper.**

***Index Terms*—CAD, embedded RF components, LTCC, optimization, space mapping.**

I. INTRODUCTION

LOW temperature cofired ceramic (LTCC) technology provides a unique and versatile approach to highly integrated radio frequency (RF) and microwave multi-chip-modules (MCMs) for various wireless communication products. It has been well understood, in the industry, that the three major aspects that decisively affect the performance, size and cost of a MCM are *package*, *interconnect* and *discrete passives*. With its distinct advantages in low loss substrate, ultra thin multilayer structure and flexible interconnection between layers, LTCC technology, by providing harmonic bed for integrated circuits (ICs) (digital and analog), die packaging, and embedded passives and accessories including antennas, is an optimal solution when the three aspects are considered. As far as interconnect is concerned, LTCC offers the capability of fine pitch (as fine as 2 mils) on thin substrate layers (as thin as 1.5 mils) of high dielectric constant, up to 50 layers. The technology allows the replacement of many discrete and surface-mounted passive components, such as capacitors and inductors, by buried components inside the ceramic substrate. As the result, the overall size of a RF system can be significantly shrunk. A good example of recent applications would be Ericsson's Bluetooth RF module, which is entirely built in an LTCC substrate [1]. Nevertheless, the technology also brings in tremendous challenges to the designers. One of the major challenges to confront is how to efficiently optimize a buried multi-layer RF passive circuit such as a filter through full-wave electromagnetic (EM) simulation tools.

The space mapping (SM) technique originally proposed by J. Bandler *et al.* [2], [3] has provided an effective optimization technique for RF and microwave circuit designs in general. In the SM method, an optimization problem is converted into a zero-finding problem of a nonlinear equation. By using Broyden's formula [4] in solving the nonlinear equation, the expensive numerical derivatives, which are required in conventional gradient based optimizations, are avoided. In other words, an accurate but computationally intensive EM fine model is used sparingly only to calibrate a less accurate but efficient coarse model in the zero-finding problem. Having employed Broyden's formula, a rapid convergence of the fine model is expected after each fine-model simulation while the bulk of the computation involved in optimization is carried out in the coarse model space for parameter extraction.

When the coarse model comes with the same ingredients as those of the fine model, say the same EM model with different mesh density; Broyden's formula can be applied directly. However, when the physical content and the dimensions in the coarse and the fine models mismatch, the Broyden's formula in the flow chart of the prior art is no longer directly applicable. For such practical scenario, people in the field lack a general guideline on how to effectively use the SM. The implementation of the SM technique is considered as a 'black art' for many engineering optimization problems. Since the circuit dimension only takes a small fraction of the wavelength of the working frequency in LTCC RF circuits, an LC lumped element circuit model serves very well as the coarse model, in which the ingredients of the coarse model (L and C) are different from those of

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the full-wave EM fine model. Therefore, it is highly desirable to have a systematic scheme such that the implementation of the SM technique is straightforward.

In this paper, a systematic knowledge embedded SM technique is introduced. In this new scheme, a buffer space is established between the original coarse and fine model spaces based on available basic formula (knowledge) derived from electromagnetic theory. The buffer space makes up the mismatch of the ingredients of the two spaces and enables the SM technique to be ideal for designing LTCC RF passives. In other words, the new implementation explicitly separate out two main aspects in the coarse model the equivalent circuit aspect and the relation between the equivalent circuit components and the physics (knowledge). This separation brings in three major advantages:

1) presenting the implementation of knowledge in the SM technique in a way that is much easier to understand by every body in the field;
2) providing the new freedom in manipulating the coarse model such that the initial optimization of the coarse model and the parameter extraction process can be performed in the equivalent circuit model using any available circuit simulator without returning to the variable space of the fine model;
3) establishing a possible road map for a generic SM implementation.

The relevant formulas (knowledge) that are usable for LTCC passive designs will be also discussed in this paper with emphasis on practical applications. The detail of the new knowledge embedded SM scheme is given after a brief review of the original SM technique. Two design examples of LTCC embedded filters are illustrated demonstrating that the new implementation scheme can greatly facilitate the application of the original SM for LTCC RF circuit design.

II. Aggressive Space Mapping (ASM) Algorithm: A Brief Review

In the original ASM technique, it is assumed that there are two simulation models for the same physical problem available:

1) an accurate but time-consuming model, which is called fine mode;
2) a rough but efficient model, namely coarse model.

The idea of space mapping algorithm is to optimize the original physical model to satisfy a set of given specifications by dragging its corresponding coarse model close to the optimized coarse model whose responses satisfy all the required specifications. Such scheme is superior to optimizing the physical model directly using the expensive gradient based optimizations because there is no requirement for the derivative information of the fine model.

Let $x_c^{(j)}$ be a point in coarse model space and $x_f^{(j)}$ be the corresponding point in the fine model space at step j of ASM process; and $x_c^{(*)}$ be the point in coarse model space whose response $R_c\left(x_c^{(*)}\right)$ is optimal. The implementation of ASM process can be described by the following steps [2]:

`Step 0. Initialize` $x_f^{(1)} = x_c^{(*)}$ `and find` $x_c^{(1)}$ `by enforcing` $\left\|R_f\left(x_f^{(1)}\right) - R_c\left(x_c^{(1)}\right)\right\| < \varepsilon$

`Step 1. Set` $B_1 = [I]$ `and define` $f^{(1)} = x_c^{(1)} - x_c^{(*)}$, `stop if` $\|f^{(1)}\| = \left\|x_c^{(1)} - x_c^{(*)}\right\| < \eta$, `otherwise`

`Step 2. Solve` $B_j \Delta x_f^{(j)} = -f^{(j)}$ `for` $\Delta x_f^{(j)}$ `and` $j \geq 1$

`Step 3. Update the fine model` $x_f^{(j+1)} = x_f^{(j)} + \Delta x_f^{(j)}$

`Step 4. Evaluate` $R_f\left(x_f^{(j+1)}\right)$ `and determine` $x_c^{(j+1)}$ `by enforcing` $\left\|R_f\left(x_f^{(j+1)}\right) - R_c\left(x_c^{(j+1)}\right)\right\| < \varepsilon$

`Step 5. Compute` $f^{(j+1)} = x_c^{(j+1)} - x_c^{(*)}$, `stop the process if` $\|f^{(j+1)}\| < \eta$, `otherwise,`

`Step 6. Update the approximated Jacobian matrix` B_j `using Broyden's formula`

$$B_{j+1} = B_j + \frac{f^{(j+1)}\left(x_f^{(j+1)} - x_f^{(j)}\right)^T}{\left(x_f^{(j+1)} - x_f^{(j)}\right)^T\left(x_f^{(j+1)} - x_f^{(j)}\right)}$$

`Step 7. Set` $j = j + 1$; `go to step 2.`

It can be observed that the physical content and the dimensions of the coarse model vector $x_c^{(j)}$ and the fine model vector $x_f^{(j)}$ need to be the same so that the approximated Jacobian matrix B_{j+1} at every iteration can be a well-defined and inversable square matrix. This is judged by the content and the dimensions of the error space $f^{(j+1)}$ since Broyden's formula for updating the approximated Jacobian matrix relies on the correction reference of the error at the latest step. The simplest implementation of SM is to use a coarse grid EM model as the coarse model and a denser grid EM model as the fine model. In such implementation, the variables for the coarse and fine models are the same geometric parameters.

III. Explicit Knowledge Embedded Space Mapping

Since the size of a RF LTCC circuit is much smaller than the working wavelength, an LC lumped element circuit model is often used in the initial design. However, in an EM fine model the variables are geometric dimension parameters. Therefore, the problems arise when a lumped circuit model is mapped to an EM fine model in the original ASM scheme if no embedded knowledge is introduced:

1) $x_f^{(1)} = x_c^{(*)}$ in step 0 is no longer applicable;
2) the approximated Jacobian matrix B_j in step 2 and 6 is a nonsquare matrix with mixed element dimensions.

Particularly, the relation of $B_1 = [I]$ is inappropriate at step 1 since the coarse model can not be mapped to the fine model directly in such case. As the result, it is virtually impossible to solve the equation $B_j \Delta x_f^{(j)} = -f^{(j)}$ for $\Delta x_f^{(j)}$ in step 2.

The predicament can be resolved by introducing a buffer space that is embedded with known knowledge of physics into the SM scheme. From a rich electromagnetic CAD literature, it is not difficult to find appropriate formulas (knowledge) to calculate circuit element values from given physical dimensions for most of LTCC basic circuit elements. We denote the knowledge relations as K or $x_c = K(x_{cf})$, which usually is a set of nonlinear equations in close form and its inversion K^{-1} or $x_{cf} = K^{-1}(x_c)$ can be uniquely determined in a confined range of K. Note that the variable space $\{x_{cf}\}$ is usually the corresponding dimension variables of the circuit parameter space $\{x_c\}$ and shares the same physical contents and dimensions as those of the variable space $\{x_f\}$ in the fine model. The dimension of $\{x_{cf}\}$ and that of $\{x_c\}$ is not necessarily the same and K^{-1} is just a symbol for inverse relation. Having introduced K^{-1}, a new explicit implementation of embedded knowledge SM scheme can be described as

`Step 0. Set` $x_{cf}^{(*)} = K^{-1}\left(x_c^{(*)}\right)$`, initialize` $x_f^{(1)} = x_{cf}^{(*)}$ `and find` $x_c^{(1)}$ `by enforcing` $\left\|R_f\left(x_f^{(1)}\right) - R_c\left(x_c^{(1)}\right)\right\| < \varepsilon$

`Step 1. Set` $B_1 = [I]$ `and determine` $x_{cf}^{(1)} = K^{-1}\left(x_c^{(1)}\right)$`; defining` $f^{(1)} = x_{cf}^{(1)} - x_{cf}^{(*)}$`, stop if` $\|f^{(1)}\| = \left\|x_{cf}^{(1)} - x_{cf}^{(*)}\right\| < \eta$`. Otherwise`

`Step 2. Solve` $B_j \Delta x_f^{(j)} = -f^{(j)}$ `for` $\Delta x_f^{(j)}$ `and` $j \geq 1$

`Step 3. Update the fine model` $x_f^{(j+1)} = x_f^{(j)} + \Delta x_f^{(j)}$

`Step 4. Evaluate` $R_f\left(x_f^{(j+1)}\right)$ `and determine` $x_c^{(j+1)}$ `by enforcing` $\left\|R_f\left(x_f^{(j+1)}\right) - R_c\left(x_c^{(j+1)}\right)\right\| < \varepsilon$ `and consequently obtain` $x_{cf}^{(j+1)} = K^{-1}\left(x_c^{(j+1)}\right)$

`Step 5. Compute` $f^{(j+1)} = x_{cf}^{(j+1)} - x_{cf}^{(*)}$`, stop the process if` $\|f^{(j+1)}\| < \eta$`. Otherwise,`

`Step 6. Update the approximated Jacobian matrix using Broyden's formula`

$$B_{j+1} = B_j + \frac{f^{(j+1)}\left(x_f^{(j+1)} - x_f^{(j)}\right)^T}{\left(x_f^{(j+1)} - x_f^{(j)}\right)^T\left(x_f^{(j+1)} - x_f^{(j)}\right)}$$

`Step 7. Set` $j = j+1$`; go to step 2.`

Where $R_f(\cdot)$ and $R_c(\cdot)$ are the responses of the fine and the coarse models, respectively. As illustrated in Fig. 1, by introducing the embedded knowledge space $\{x_{cf}\}$ as a buffer space between the coarse model variable space $\{x_c\}$ and the fine model variable space $\{x_f\}$, the content and the dimensions of the error vectors $f^{(j+1)}$ in the knowledge space match to those of the variable vector in the fine model. Therefore, the approximated Jacobian matrix B_j can be updated in a normal sense. It is worth mentioning that $x_c^{(*)}$ is obtained in the coarse model without worrying about the matching between its physical content and that of the fine model. To gain a better understanding of the procedure, the flowchart of the scheme is shown in Fig. 2.

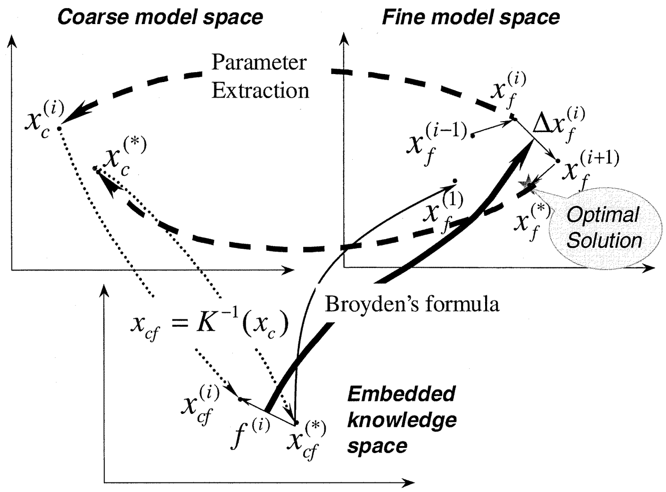

Fig. 1. Illustration of the explicit implementation of the embedded knowledge in space mapping: thick dashed lines refer to parameter extraction; thin dotted lines refer to K^{-1}; thin solid line refers to the direct assignment and thick solid lines refer to update of the fine model by using Broyden's formula.

IV. Embedded Knowledge for Design of LTCC RF Passives

The embedded knowledge space can be built by various means. The elements in the space are kinds of relations between physical dimensions and coarse model component values, such as inductance and capacitance. The relations can be given by either look-up tables or closed form formulas. For simple embedded passives, the following well-developed formulas serve the purpose very well.

A. Inductance Modeling

How to calculate the inductance of a conducting strip, a via-hole and mutual inductance between two strips is one of the major concerns in LTCC passive designs. Assuming uniform current densities over two conducting strips, the mutual inductance between the two strips as shown in Fig. 3(a) can be found from the Neumann's formula as [5]

$$\begin{aligned} M = \frac{\mu}{4\pi}\cdot\frac{1}{ad}\Bigg[\Bigg[&\frac{x^2-P^2}{2}z\ln\left(z+\sqrt{x^2+P^2+z^2}\right)\\ &+\frac{z^2-P^2}{2}x\ln\left(x+\sqrt{x^2+P^2+z^2}\right)\\ &-\frac{1}{6}\left(x^2-2P^2+z^2\right)\sqrt{x^2+P^2+z^2}\\ &-xPz\tan^{-1}\frac{xz}{P\sqrt{x^2+P^2+z^2}}\Bigg]\\ &\times(x)_{E+d-a,E}^{E-a,E+d}\Bigg](z)_{l_3+l_2-l_1,l_3}^{l_3-l_1,l_3+l_2} \end{aligned} \quad (1)$$

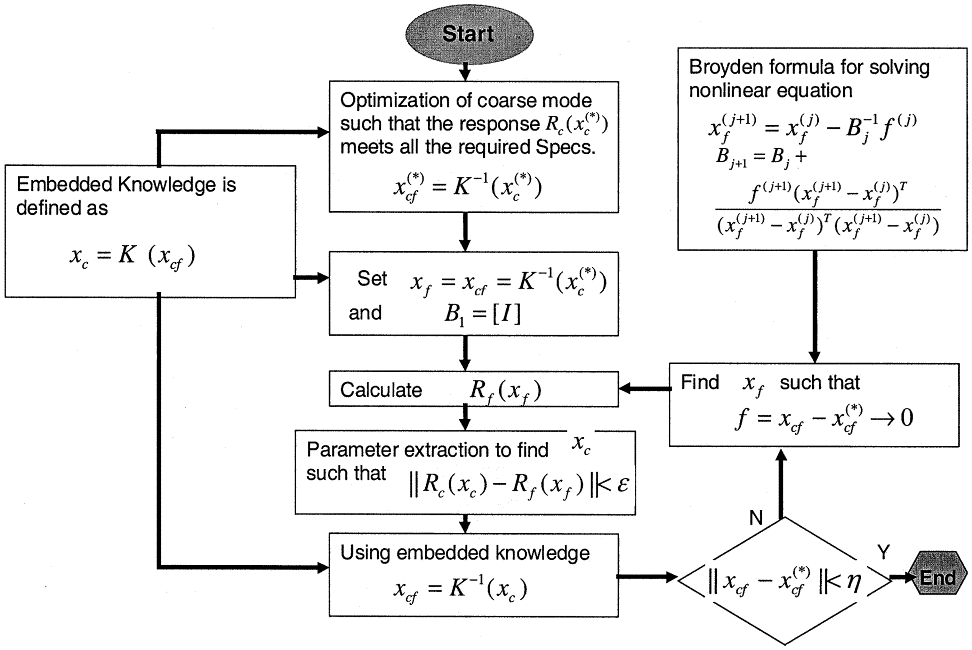

Fig. 2. Flowchart of the explicit implementation of embedded knowledge in space mapping scheme.

where $\left[[f(x,z)](x)_{q_2,q_4}^{q_1,q_3}\right](z)_{s_2,s_4}^{s_1,s_3} \equiv \sum_{i=1}^{4}\sum_{k=1}^{4}(-1)^{i+k} f(q_i, s_k)$.

The self-inductance of a conducting strip can be calculated from the above formula by setting $a = d$ and $E = P = l_3 = 0$ in (1).

In an LTCC circuit, it is common that there are large ground planes sitting below and above metal strips. In addition, the inductance of a via-hole is not negligible in many practical applications. It can be shown that the above general formula can be employed to deal with these practical cases, where the ground planes are large enough for image theory to hold.

Case 1) *One ground plane system*

In such case, we may obtain a new formula for the mutual inductance calculation, in which the effect of the bottom ground plane has been included by using the image theory. The formula for calculating the mutual inductance between the two strips with a bottom ground plane can be expressed as

$$M_{\text{total}} = M(P, \ldots) - M(P_{\text{image}}, \ldots). \tag{2}$$

Case 2) *Top and bottom ground planes system*

The calculation of the inductance for this case is similar to that of case 1. But this time, we have a set of images instead of just one. The locations of this set of images can be found by using simple ray tracing technique. Therefore, the resultant mutual inductance is

$$M_{\text{total}} = M(P, \ldots) - M(P_{\text{image1}}, \ldots) + M(P_{\text{image2}}, \ldots) - \cdots \tag{3}$$

Case 3) *Inductance for via-holes*

Sometimes, there are needs to calculate mutual/self inductance between vias. It is most readily obtained by integrating (1) over y direction (refer to Fig. 3(b). The mutual inductance between two vias is

$$M_{\text{via}} = \frac{\mu}{4\pi}\int_{P-r_2}^{P+r_2}\int_{-r_1}^{r_1} ad \cdot M(P, \ldots) dy_1 dy_2. \tag{4}$$

Note that a, d and M are now functions of y_1 and y_2. This integral can be calculated numerically to obtain the inductance between two vias.

Fig. 3(c) shows the inductance value calculated by Neumann's formula and extracted from EM calculated response, demonstrating that Neumann's formula can serve as an element in the embedded knowledge space.

B. Capacitance Modeling

When two conducting patches are closely placed, parallel plate capacitance formula serves a good approximation model. More sophisticated models for more complex configurations can be derived, for instance, through the synthetic asymptote approach. For example, the capacitance formula for a conducting patch located at the air-substrate interface above a large ground plane can be found as [6]

$$C = \varepsilon_0 \left[\left(\frac{\varepsilon_r A}{t}\right)^n + \left(\frac{(\varepsilon_r + 1)}{2} c_f \sqrt{8\pi A}\right)^n\right]^{1/n} \tag{5}$$

where the shape factor $c_f \approx 0.9$, for square plates and plates of many common shapes, t is the thickness of the substrate be-

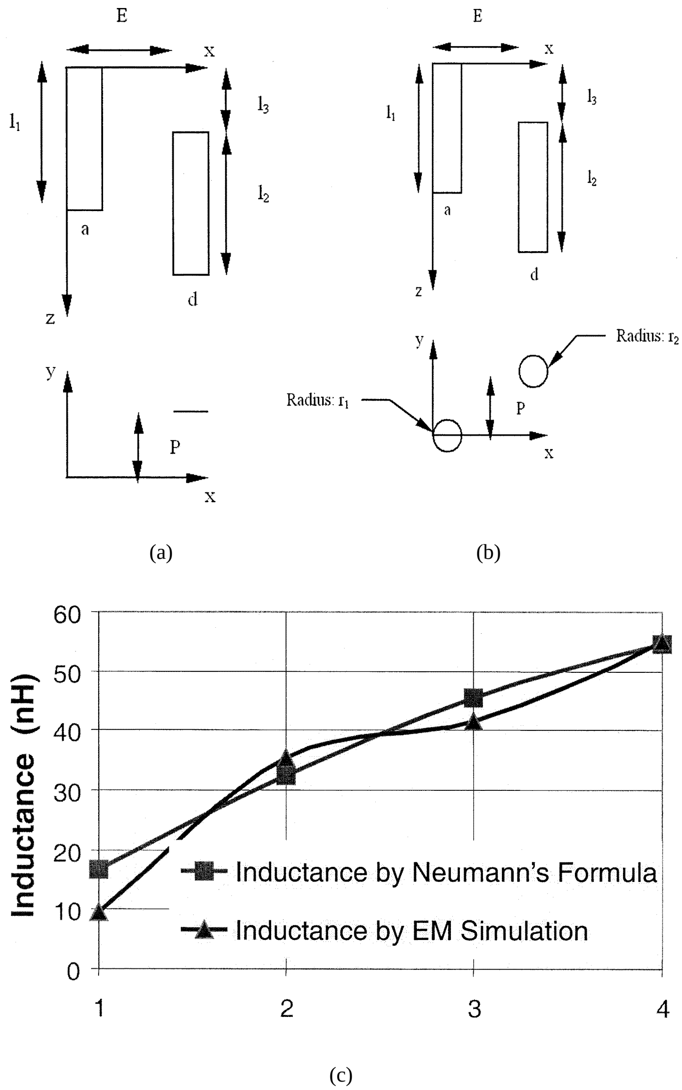

Fig. 3. (a) Geometry for two parallel strips for inductance calculation. (b) Geometry for calculation of mutual inductance of two parallel vias. (c) Comparison of inductance value calculated by Neumann's formula and EM simulation for a five-turn spiral inductor with strip width = 0.2 mm, spacing = 0.2 mm and the distance to ground = 1 mm.

tween two plates and A is the area of the patch. It was claimed that when the make up exponent $n = 1.114$, the maximum error can be reduced to 1%.

V. Design Examples

A two-pole LTCC multilayer filter for Bluetooth applications is designed using the proposed explicit implementation scheme. The filter structure was originally proposed by Dr. Dick Smith [7]. The physical layout shown in Fig. 4(a) contains nine geometric variables while its equivalent circuit shown in Fig. 4(b) has only eight variables in this example. The equivalent circuit serves as the coarse model and the CAD formulas discussed in Section IV are used as knowledge K in applying the proposed implementation scheme. Note that some of the geometric variables are redundant and used to relax the dimension constraints here. Fig. 5(a) shows the response of optimized coarse model $R_c\left(x_c^{(*)}\right)$, the EM simulation of the fine model of the initial guess $R_f\left(x_f^{(1)}\right)$ and the response $R_c\left(x_c^{(1)}\right)$, which is the result of a curve fitting of $R_f\left(x_f^{(1)}\right)$ through which the coarse model parameters $x_c^{(1)}$ is extracted. As illustrated in Fig. 5(a)–(c), the proposed scheme only takes 3 EM simulation sweeps to achieve an acceptable solution from the initial design. In this example, the commercial IE3D planar circuit EM simulator was used. Each simulation sweep took about 30 min on a 700 MHz PC. A similar solution are obtained through a conventional gradient based optimization by taking 20 iterations (10 EM simulation sweeps are required for each iteration) or 200 EM simulation sweeps. It should be mentioned that in order to well fit the fine model, which has certain conductor loss, a small resistor (say 0.4 Ω) is added to the inductors in the coarse model. The added resistance value should match the insertion loss of the coarse to that of the fine models.

A three-pole LTCC multilayer filter that is targeted to W-CDMA applications is also designed using the proposed scheme. The physical layout of the multilayer filter and its equivalent circuit model are shown in Fig. 6. In this design the filter contains three LC tanks and is with 13 geometric variables while as there are 11 parameters in the coarse models. The lateral dimensions of the filter are about 210 by 120 mils and the thickness of 36 mils. Again, an LC circuit model is used as the coarse model, in which the couplings between components are neglected except the designated coupling between L1 and L2.

The optimum coarse model response is shown in Fig. 7(a) along with the response of the initial fine model solution $R_f\left(x_f^{(1)}\right)$ and the corresponding $R_c\left(x_c^{(1)}\right)$. A fairly large discrepancy can be seen between the response of the initial fine model $R_f\left(x_f^{(1)}\right)$ and the target template $R_c\left(x_c^{(*)}\right)$. After using Broyden's formula once in the proposed SM scheme the response of the fine model $R_f\left(x_f^{(2)}\right)$ rapidly converges to $R_c\left(x_c^{(*)}\right)$ with right center frequency and bandwidth, as shown in Fig. 7(b). It can be observed that the procedure only takes 3 EM simulation sweeps to bring the design close enough for further fine-tuning.

Due to the discrepancy between the coarse model and the reality in the fine model, the coarse model can not fit to the fine model perfectly well. This deficiency slows down the convergence of the SM scheme for fine-tuning. In order to improve the return loss in the pass band of interest a fine-tuning optimization using a conventional gradient based optimization was carried out with a very litter effort. This topic is beyond the scope of this paper and therefore is not discussed here. Nevertheless, the coarse model should reflect the parasitics as much as possible to well approximate the fine model. This is a very critical issue particularly when the fine model contains tight mutual couplings.

The comparisons of $R_c\left(x_c^{(*)}\right)$ with $R_f\left(x_f^{(3)}\right)$ and the responses after fine-tuning are shown in Fig. 7(d) with specification marks. Two side notes are worth mentioning for this ex-

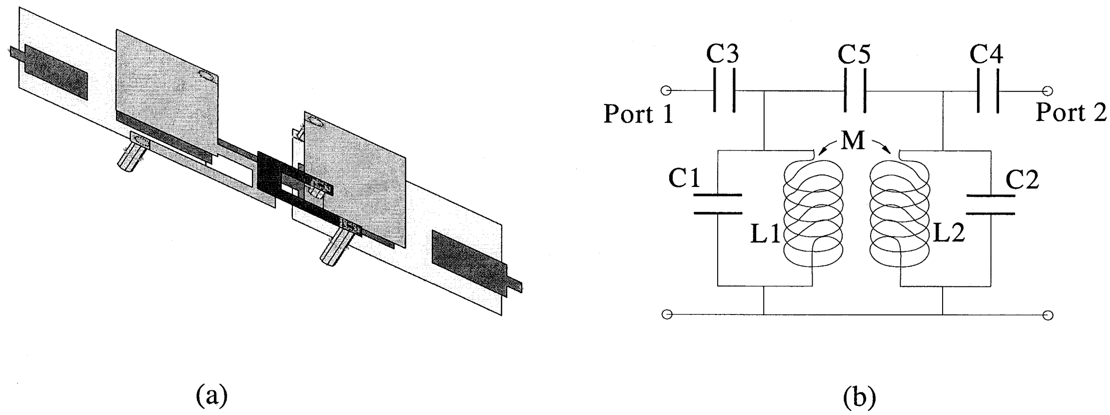

Fig. 4. Two-pole LTCC filter: (a) the physical layout and (b) the equivalent circuit model.

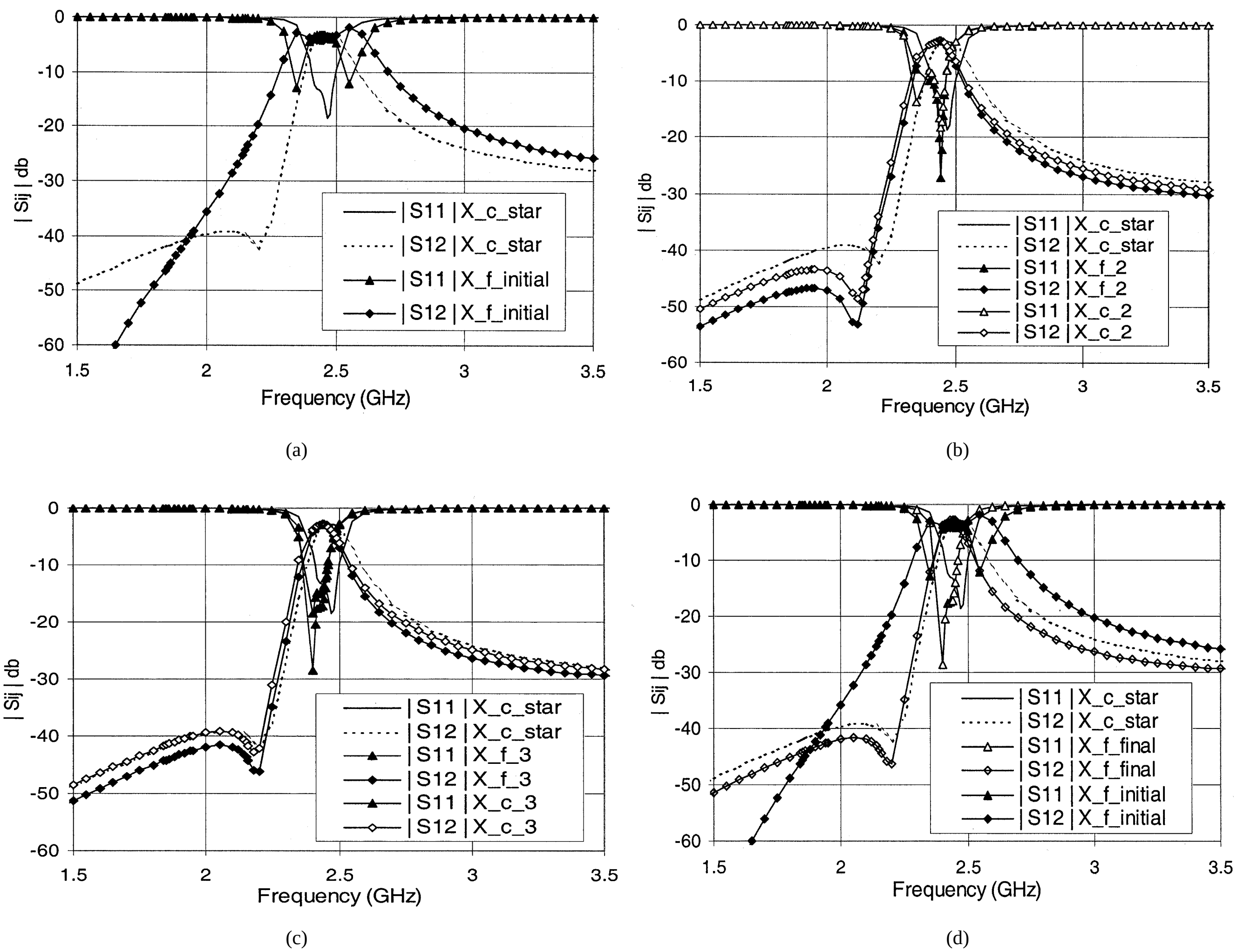

Fig. 5. (a) Comparison of $R_c\left(x_c^{(*)}\right)$ with $R_f\left(x_f^{(1)}\right)$ and $R_c\left(x_c^{(1)}\right)$. (b) The comparison of $R_c\left(x_c^{(*)}\right)$ with $R_f\left(x_f^{(2)}\right)$ and $R_c\left(x_c^{(2)}\right)$. (c) The comparison of $R_c\left(x_c^{(*)}\right)$ with $R_f\left(x_f^{(3)}\right)$ and $R_c\left(x_c^{(3)}\right)$. (d) The comparison of $R_c\left(x_c^{(*)}\right)$ with the initial and final responses of the fine model.

ample: (1) a great deal of efforts have also been paid to optimize the circuit using conventional gradient based optimization routine such as MINMAX with $x_f^{(1)}$ as the initial starting point and the results show no sign of success. And (2) since the very little loss is considered in the full wave EM simulation (fine model), the insertion loss predicted by the EM simulation is not practical. Nevertheless, the prediction of the insertion should not be the issue in this content of discussion.

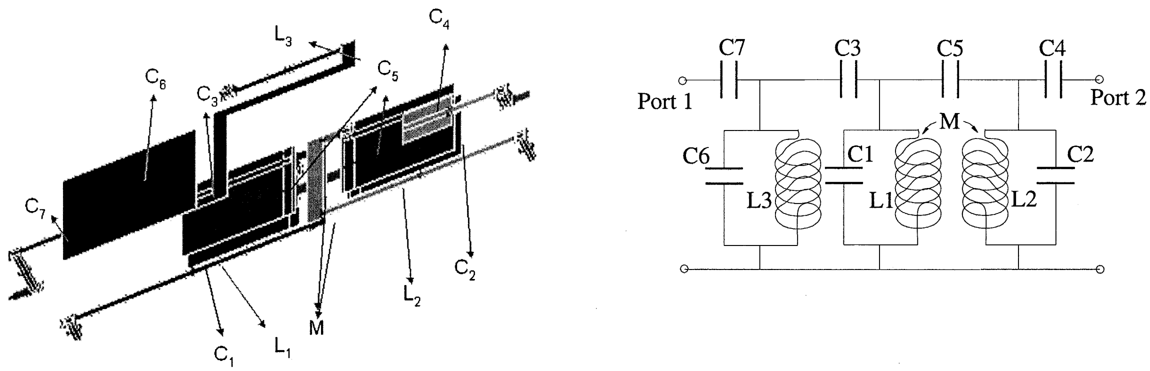

Fig. 6. Three-pole LTCC filter: (a) the physical layout and (b) the equivalent circuit model.

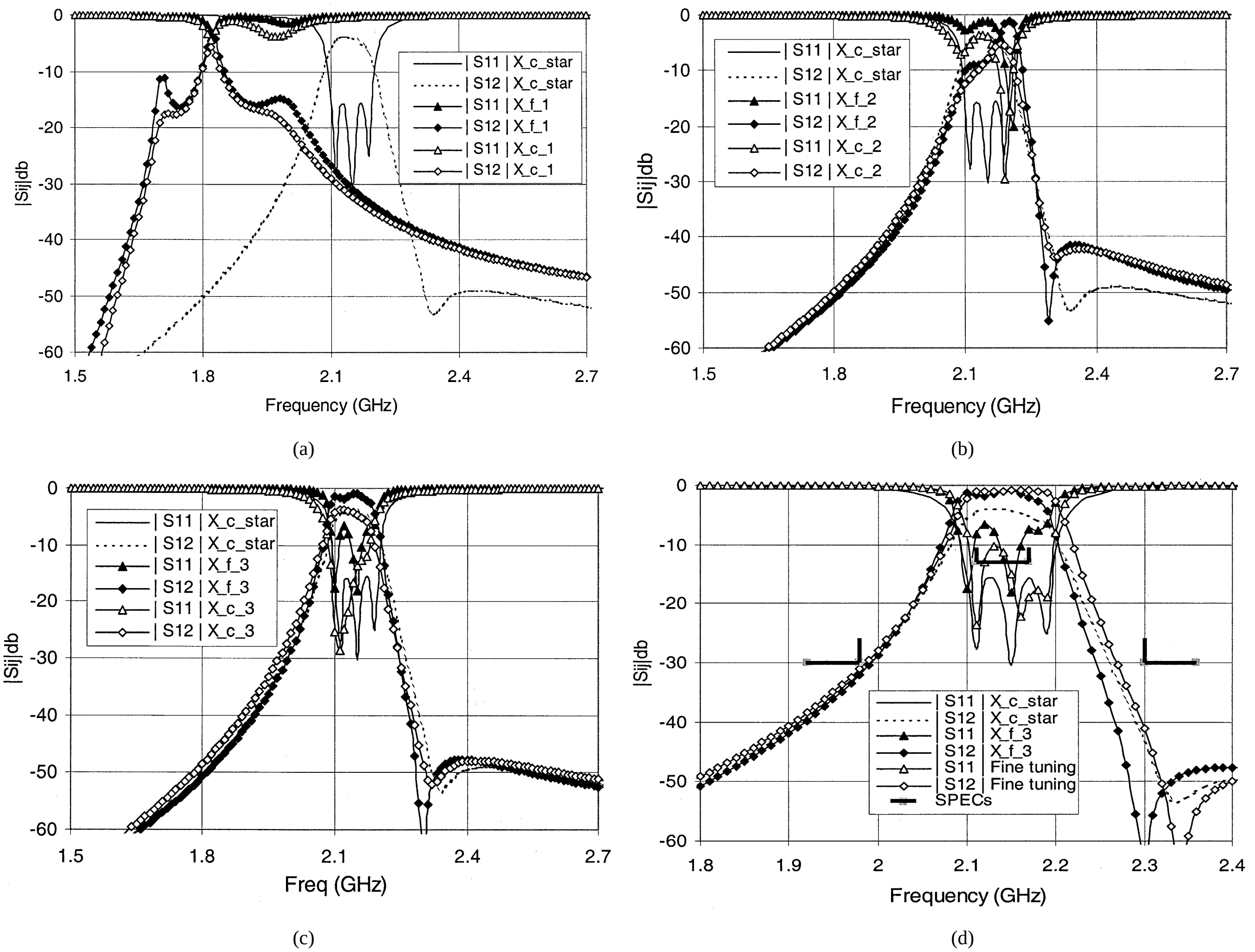

Fig. 7. (a) Comparison of $R_c\left(x_c^{(*)}\right)$ with $R_f\left(x_f^{(1)}\right)$ and $R_c\left(x_f^{(1)}\right)$. (b) The comparison of $R_c\left(x_c^{(*)}\right)$ with $R_f\left(x_f^{(2)}\right)$ and $R_c\left(x_f^{(2)}\right)$. (c). The comparison of $R_c\left(x_c^{(*)}\right)$ with $R_f\left(x_f^{(3)}\right)$ and $R_c\left(x_f^{(3)}\right)$. (d) The comparison of $R_c\left(x_c^{(*)}\right)$ with $R_f\left(x_f^{(3)}\right)$ and the responses after fine tuning with specification marks.

VI. Conclusion

In this paper, we have presented a new explicit knowledge embedded space mapping (SM) optimization technique. The new scheme systematically integrates the available RF circuit CAD formula (knowledge) with the efficient SM optimization technique by introducing a buffer space, namely embedded knowledge space, between the original coarse model space and the fine model space. Therefore, the model in the coarse space can be in any form and with any physical content at convenience. The knowledge buffer space translates the ingredients in the coarse model space to those in the fine model space so that the coarse space can be mapped to the fine space systematically. As the result, the new explicit technique provides a great deal of flexibility in choosing the coarse model in using the SM technique. This feature is significantly useful in practical applications, particularly for design of LTCC RF passive circuits. Although the application is emphasized on the design of LTCC RF passive circuits in this paper, the new scheme is generic for any other RF circuit and packaging designs exploiting the SM technique, where the coarse model possesses different physical content and dimensions from those of the fine model. The new implementation scheme is successfully demonstrated through the design of two LTCC multilayer filters for wireless communications applications.

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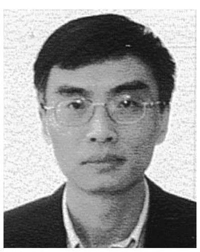

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