AGGRESSIVE SPACE MAPPING FOR ELECTROMAGNETIC DESIGN

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ABSTRACT

We propose a new aggressive Space Mapping strategy for electromagnetic (EM) optimization. Instead of waiting for upfront EM analyses at several base points, it exploits every available EM analysis using the classical Broyden update, producing dramatic results right from the first step. A high-temperature superconducting filter design solution emerges after fewer EM analyses than the number of designable parameters! For the first time, Space Mapping is extended to the parameter extraction phase, overcoming severely misaligned starting points induced by inadequate empirical models.

INTRODUCTION

Our recent exposition of Space Mapping (SM) [1-3] aroused unprecedented excitement in the microwave community. The SM concept combines the computational expediency of empirical engineering models (which embody expert knowledge accumulated over many years) and the acclaimed accuracy of electromagnetic (EM) simulators to facilitate automated design optimization within a practical time frame.

In our original pioneering work, upfront EM analyses were required at a number of base points in order to establish a full-rank initial approximation of the mapping between the empirical and EM spaces. In that scheme, the number of base points and correspondingly the number of upfront EM analyses increase in proportion to the number of designable parameters. Furthermore, since the initial base points are generated by perturbing the starting point in the EM space, they are unlikely to produce a substantially better design than the starting point itself. In other words, the initial EM analyses themselves become a time-consuming and possibly unproductive effort.

We present a new SM approach which employs an aggressive strategy for updating the SM approximation. A simple, straightforward initial approximation is assumed. Then, every EM analysis is targeted directly at achieving the best design and the results are immediately utilized to improve the approximation using the classical Broyden update [4]. In this way, we expect to obtain a progressively improved design after each EM analysis.

One of the key steps in SM is to determine pairs of corresponding EM and empirical models through parameter extraction. From the EM simulation results, we need to extract the parameter values of the corresponding empirical model. This can be a serious challenge, especially at the starting point, when the responses produced by EM analysis and by the empirical model may be severely misaligned. We apply, for the first time, SM to parameter extraction by introducing two new algorithms for automated Frequency Space Mapping (FSM): a sequential mapping algorithm and an exact penalty function algorithm. They offer a powerful means of overcoming the problems of local minima and data misalignment.

Our new theory and techniques are demonstrated by applications to the EM design of a low-loss, narrow-bandwidth high-temperature superconducting (HTS) microstrip filter [3, 5]. From a poor starting point, a solution emerges after only 4 EM analyses carried out at only 7 frequency points. It requires fewer EM analyses than the number of designable parameters (6)! We utilize the OSA90/hope optimization system with the Empipe interface [6] to the *em* field simulator [7].

OVERVIEW OF THE SPACE MAPPING CONCEPT

We consider models in two distinct spaces: the optimization space, denoted by X_{OS}, and the EM space, denoted by X_{EM}. We represent the model parameters in these spaces by x_{OS} and x_{EM}, respectively. The X_{OS} model can be an analytical/empirical model [3], or a coarse-grid EM model [1, 2].

We assume that the X_{OS} model responses, denoted by $f_{OS}(x_{OS})$, are much faster to calculate but less accurate than the X_{EM} model responses, denoted by $f_{EM}(x_{EM})$. We wish to find a mapping $T(x_{EM})$ such that

$$\| f_{OS}(T(x_{EM})) - f_{EM}(x_{EM}) \| \le \epsilon \quad (1)$$

where $\|\cdot\|$ is a suitable norm and ϵ is a small positive constant.

We perform optimization in X_{OS} to obtain the optimal design x_{OS}^* and use SM to find the mapped solution in X_{EM} as

$$\bar{x}_{EM} = T^{-1}(x_{OS}^*) \quad (2)$$

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assuming that T is invertible. This is illustrated in Fig. 1. We use $\bar{x}_{EM}$ instead of x^*_{EM} since the mapped solution may not be the true optimum in X_{EM}.

In our original work [1-3], we obtain the initial approximation of T by performing EM analyses at a set of base points around the starting point given by

$$x^1_{EM} = x^*_{OS}. \tag{3}$$

These EM analyses represent an upfront effort before any significant improvement over the starting point can be expected.

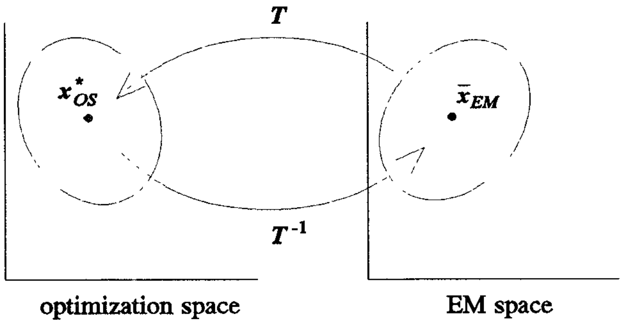


Fig. 1. Illustration of SM. The inverse mapping T^{-1} maps the optimal design x^*_{OS} to $\bar{x}_{EM}$ in the EM space.

SPACE MAPPING WITH THE BROYDEN UPDATE

We assume that x_{OS} and x_{EM} have the same dimension. We further assume that the mapping T can be linearized locally, such that at the ith step we have

$$T(x^i_{EM} + h) \approx T(x^i_{EM}) + A_i h. \tag{4}$$

We target every EM analysis at the optimal design in the sense that x^i_{EM} is generated not merely as a base point for establishing the mapping, but as our current best estimate of the mapped solution as defined by (2). The mapping T is found iteratively starting from $T_0(x) = x$.

At the starting point we let $x^1_{EM} = x^*_{OS}$ and $A_1 = 1$. At the ith step, we obtain x^i_{EM} by applying (2) using the current estimate of T, namely T_i. If the EM analysis at x^i_{EM} produces the desired responses, then our mission is accomplished. Otherwise, we find x^i_{OS} which corresponds to x^i_{EM} by parameter extraction, i.e., we extract x^i_{OS} through optimization in X_{OS} from the data provided by the EM analysis at x^i_{EM}.

Adapting the classical Broyden formula [4], we update the SM transformation by

$$A_{i+1} = A_i + \frac{[x^{i+1}_{OS} - x^i_{OS} - A_i h_i] h_i^T}{h_i^T h_i} \tag{5}$$

where $h_i = x^{i+1}_{EM} - x^i_{EM}$.

HTS FILTER DESIGN BY EM OPTIMIZATION

We consider the design of a four-pole quarter-wave parallel coupled-line microstrip filter, as illustrated in Fig. 2 [3]. L_1, L_2 and L_3 are the lengths of the parallel coupled-line sections and S_1, S_2 and S_3 are the gaps between the sections. The width $W = 7$ mil is the same for all the sections as well as for the input and output microstrip lines. The input and output line lengths are $L_0 = 50$ mil. The thickness of the lanthanum aluminate substrate used is 20 mil and the dielectric constant is assumed to be 23.425. The design specifications imposed on $|S_{21}|$ are as follows.

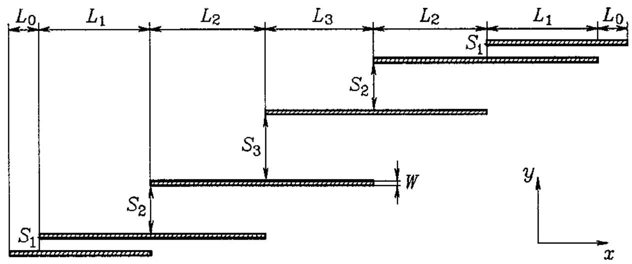


Fig. 2. The structure of the HTS filter.

$$|S_{21}| \le 0.05 \quad \text{for} \quad f \le 3.967 \text{ GHz and } f \ge 4.099 \text{ GHz}$$
$$|S_{21}| \ge 0.95 \quad \text{for} \quad 4.008 \text{ GHz} \le f \le 4.058 \text{ GHz}$$

This corresponds to a 1.25% bandwidth. L_1, L_2, L_3, S_1, S_2 and S_3 are considered as design parameters. L_0 and W are fixed. We employ both traditional analytical/empirical models built into OSA90/hope and a fine-grid Sonnet EM model. The x- and y-grid sizes for the numerical EM simulation are chosen as Δx = 1 mil and Δy = 1.75 mil. On a Sun SPARCstation 10, approximately 1 CPU hour is needed to simulate the filter at a single frequency for an on-the-grid point.

The minimax solution of the HTS filter design using OSA90/hope is listed in Table I. But, the results of an *em* analysis at this solution are significantly different from the circuit simulation results, as shown in Fig. 3. Assuming that the EM model is the more accurate one, our aim is to use SM to find a solution in the EM space which will substantially reproduce the optimal performance predicted by the empirical circuit model.

Applying our new aggressive SM algorithm with the Broyden update to the HTS filter design, we obtain the solution listed in Table I after only 4 EM analyses, requiring only 7 frequency points per EM simulation. In comparison, our original SM solution [3] required 13 EM analyses (which in itself was a breakthrough, since early attempts of direct optimization in the

TABLE I
HTS PARALLEL COUPLED-LINE MICROSTRIP FILTER DESIGN SOLUTIONS

Parameter (mil)	OSA90/hope (OS)	New SM (EM)	Original SM [3] (EM)
L_1	191.00	185.00	190.00
L_2	195.58	197.00	192.00
L_3	191.00	184.00	189.00
S_1	21.74	19.25	19.25
S_2	96.00	78.75	75.25
S_3	114.68	85.75	91.00
Number of EM Analyses	-	4	13

W and L_0 are kept fixed at 7 mil and 50 mil, respectively. The EM solutions are rounded to the nearest grid-point.

EM space failed to produce an acceptable design after consuming weeks of CPU time on EM analyses). Fig. 4 shows the filter responses of the optimal empirical model design x_{OS}^* and the new SM solution $\bar{x}_{EM}$.

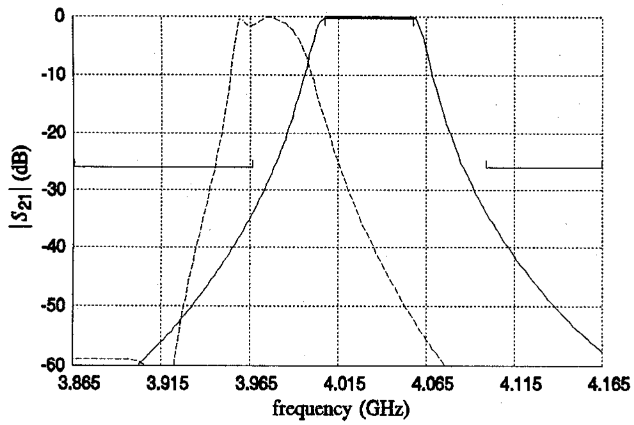
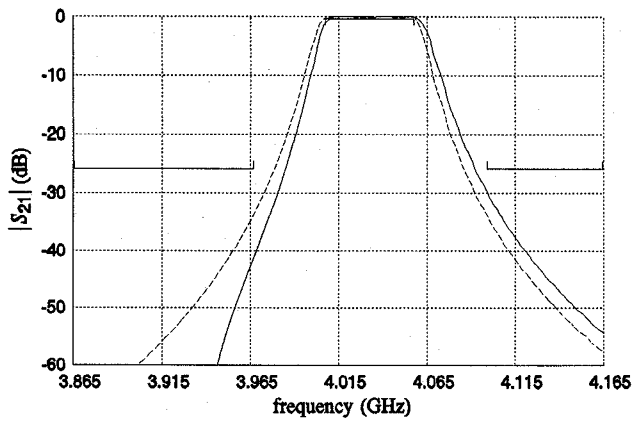
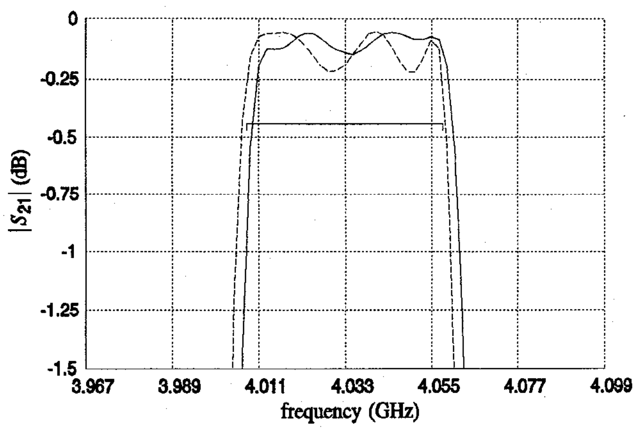


Fig. 3. The optimal $|S_{21}|$ responses obtained using OSA90/hope (——) and the corresponding ***em*** simulation results (- - -).



(a)



(b)

Fig. 4. The ***em*** simulated $|S_{21}|$ response of the HTS filter at the solution obtained using the new SM optimization method (——). The OSA90/hope empirical solution (- - -) is shown for comparison. Responses for (a) the overall band and (b) the passband in more detail.

FREQUENCY SPACE MAPPING FOR PARAMETER EXTRACTION

One of the key steps of SM involves parameter extraction. For each x_{EM} we need to find the corresponding x_{OS}. This can be a serious challenge, especially at the starting point, if the X_{OS} and X_{EM} responses are severely misaligned, such as the case shown in Fig. 5. If we perform straightforward optimization from such a starting point, the extraction process can be trapped by a local minimum, as illustrated in Figs. 6 and 7.

In Fig. 5, we notice a similarity between the shapes of f_{OS} and f_{EM}. The parameter extraction problem can be better conditioned if we can align f_{OS} and f_{EM} along the frequency axis. Hence, we introduce Frequency Space Mapping (FSM):

$$\omega_{OS} = T_\omega(\omega). \tag{6}$$

The mapping can be as simple as frequency shift and scaling given by $\omega_{OS} = S\omega + D$. At the starting point, we determine S^0 and D^0 by the following optimization

$$\underset{S^0,\, D^0}{minimize} \; \{\| f_{OS}(x_{OS}, S^0\omega + D^0) - f_{EM}(x_{EM}, \omega) \|\} \tag{7}$$

where the model parameters are not optimized and $x_{OS} = x_{EM}$. The result is illustrated in Fig. 8.

We developed two algorithms: a sequential FSM algorithm (SFSM) and an exact penalty function (EPF) algorithm. In the SFSM algorithm, we perform a sequence of optimizations in which the FSM is gradually reduced to the identity mapping and x_{OS} is optimized to achieve a match between f_{OS} and f_{EM}:

$$\underset{x_{OS}^i}{minimize} \; \{\| f_{OS}(x_{OS}^i, S^i\omega + D^i) - f_{EM}(x_{EM}, \omega) \|\} \tag{8}$$

where we update the values S^i and D^i according to $S^i = 1 + (S^0 - 1)(K - i)/K$ and $D^i = D^0(K - i)/K$, respectively, for $i = 0, 1, ..., K$. K determines the number of steps in the sequence. After optimization x_{OS}^K is the solution to the parameter extraction problem, since $S^K = 1$ and $D^K = 0$.

In the EPF algorithm, we need only one optimization

$$\underset{x_{OS}, S, D}{minimize} \; \{\| f_{OS}(x_{OS}, S\omega + D) - f_{EM}(x_{EM}, \omega) \| + \alpha_1 g_1 + \alpha_2 g_2\} \tag{9}$$

from the starting point $x_{OS} = x_{EM}$, where $g_1 = |S - 1|$, $g_2 = |D|$,

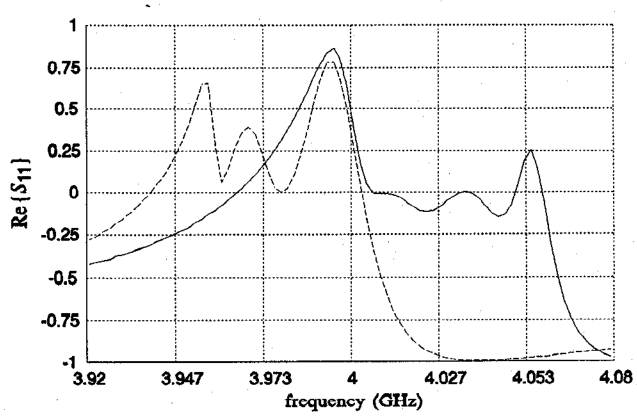


Fig. 5. Re$\{S_{11}\}$ simulated using the empirical model (——) and ***em*** (- - -) at the starting point for parameter extraction.

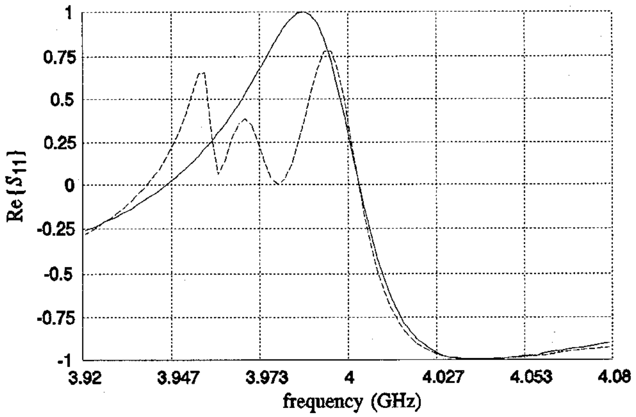


Fig. 6. Re{S_{11}} simulated using the empirical model (——) and *em* (---) at the solution of a straightforward ℓ_1 optimization (a local minimum).

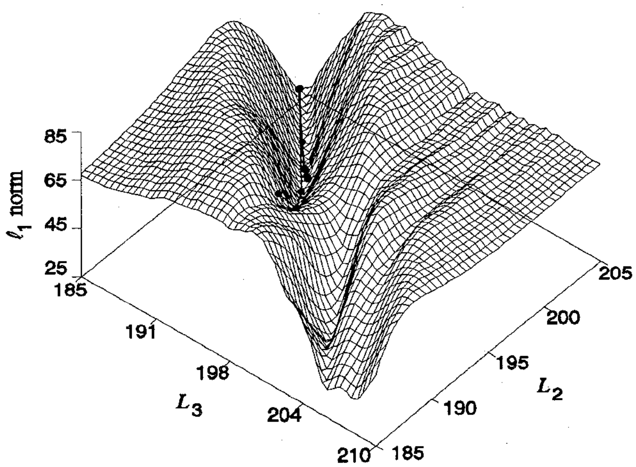


Fig. 7. Visualization of the ℓ_1 norm versus two of the model parameters L_2 and L_3, superimposed by the trace of the straightforward ℓ_1 optimization. The optimization converged to a local minimum instead of the true solution represented by the valley near the front of the graph.

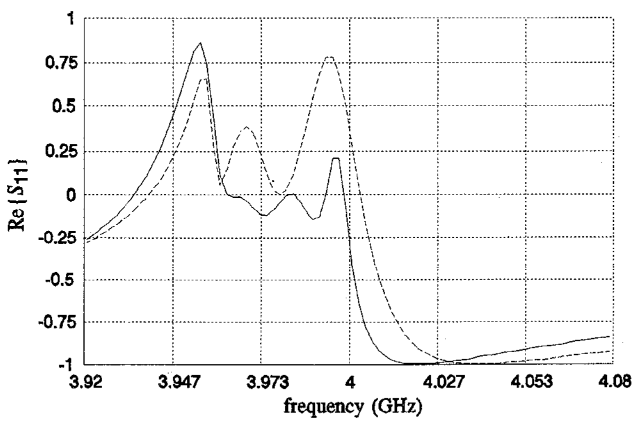


Fig. 8. Re{S_{11}} simulated using the empirical model (——) and *em* (---) at the starting point after applying the FSM algorithm. This starting point is now ready for regular parameter extraction.

$S = S^0$ and $D = D^0$. Using ℓ_1, we can obtain the *exact* solution when the factors α_1 and α_2 are sufficiently large. In our example, the exact solution is found for $\alpha_1 = \alpha_2 \geq 10$.

While the frequency transformation concept is familiar to microwave engineers, particularly filter designers, here it is defined in a novel way. Our FSM is established through an iterative process and facilitates automated compensation for inadequate modeling. This significantly improves robustness of the parameter extraction phase of the overall SM technique.

CONCLUSIONS

We have proposed a new automated SM approach which aggressively exploits every EM analysis. We have employed the classical Broyden update to target the next EM point at the optimal design. We have demonstrated significant improvement over our original SM algorithm by reducing the number of EM analyses required to obtain an HTS filter design. We have pioneered the application of the SM concept to parameter extraction by developing new FSM algorithms for overcoming poor starting points induced by inadequate empirical models.

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