

**AGGRESSIVE SPACE MAPPING  
FOR ELECTROMAGNETIC DESIGN**

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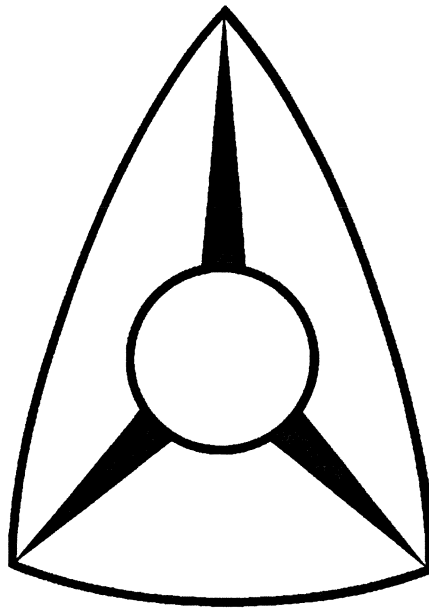
OSA-95-OS-9-V

May 10, 1995

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## **Abstract**

We present 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 utilizing 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! We extend the Space Mapping concept to the parameter extraction phase, overcoming severely misaligned responses induced by inadequate empirical models.



## **Introduction**

the Space Mapping (SM) concept combines the computational expediency of empirical models and the acclaimed accuracy of electromagnetic (EM) simulators

the original SM exploited upfront EM analyses at a number of base points

the new SM approach employs an aggressive strategy for updating the SM approximation

from a straightforward initial approximation, each EM analysis is targeted directly at improving the design and the approximation is updated using the classical Broyden update

we introduce two Frequency Space Mapping (FSM) algorithms for parameter extraction to overcome problems caused by local minima and data misalignment

we utilize the OSA90/hope optimization system with the Empipe interface to the *em* field simulator from Sonnet Software



## **The Concept of Space Mapping**

*(Bandler, Biernacki, Chen, Grobelny and Hemmers, 1994)*

we wish to find a mapping  $T(x_{EM})$  from the EM space  $X_{EM}$  to the optimization space  $X_{OS}$  such that

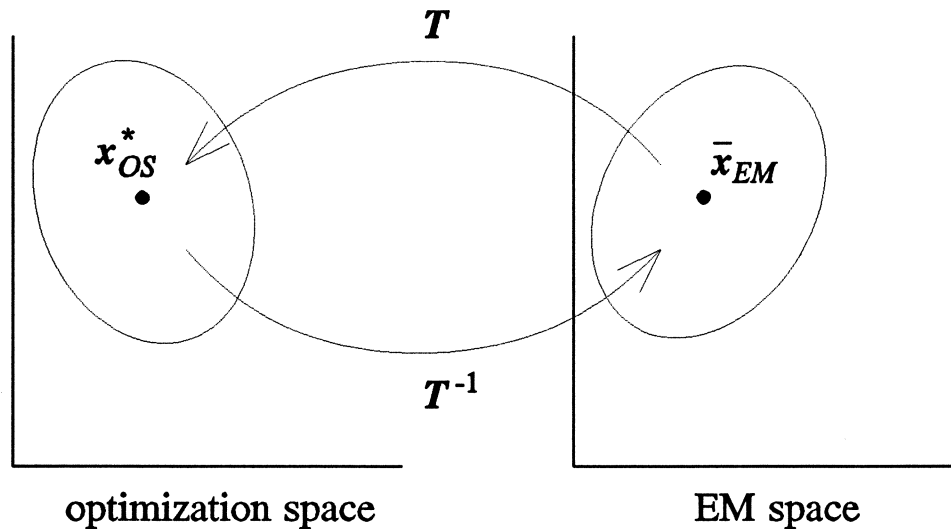
$$\|f_{OS}(T(x_{EM})) - f_{EM}(x_{EM})\| \leq \epsilon$$

where  $f_{OS}$  and  $f_{EM}$  are the circuit responses simulated by the OS and EM simulators, respectively

starting from the optimal design  $x_{OS}^*$  (in  $X_{OS}$ ) we use SM to find the mapped solution in  $X_{EM}$  as

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

assuming that  $T$  is invertible





## Space Mapping with the Broyden Update

we assume that  $x_{OS}$  and  $x_{EM}$  have the same dimensionality

the mapping  $T$  is found iteratively starting from  $T_0(x) = x$  or

$$x_{EM}^1 = x_{OS}^* \quad \text{and} \quad A_1 = 1$$

at the  $i$ th step, the mapping  $T$  is linearized locally as

$$T(x_{EM}^i + h) \approx T(x_{EM}^i) + A_i h$$

adapting the classical Broyden updating formula (*Broyden, 1965*), we improve the approximation by

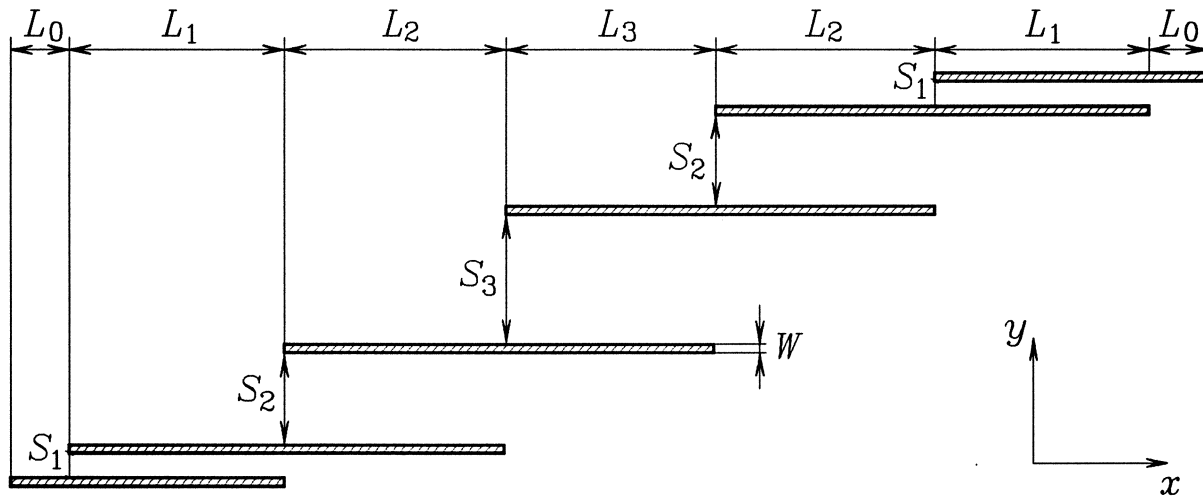
$$A_{i+1} = A_i + \frac{[x_{OS}^{i+1} - x_{OS}^i - A_i h_i] h_i^T}{h_i^T h_i}$$

where  $h_i = x_{EM}^{i+1} - x_{EM}^i$

if the EM analysis at  $x_{EM}^{i+1}$  produces the desired responses, then our mission is accomplished, otherwise, we find, by parameter extraction,  $x_{OS}^{i+1}$  which corresponds to  $x_{EM}^{i+1}$



## HTS Parallel Coupled-line Microstrip Filter (Westinghouse, 1993)



substrate (lanthanum aluminate) thickness is 20 mil and the dielectric constant is 23.425

design specifications

$$|S_{21}| \leq 0.05 \quad \text{for} \quad f \leq 3.967 \text{ GHz and } f \geq 4.099 \text{ GHz}$$

$$|S_{21}| \geq 0.95 \quad \text{for} \quad 4.008 \text{ GHz} \leq f \leq 4.058 \text{ GHz}$$

$L_1$ ,  $L_2$ ,  $L_3$ ,  $S_1$ ,  $S_2$  and  $S_3$  are the design parameters

$L_0$  and  $W$  are kept fixed at 50 mil and 7 mil, respectively



## **Space Mapping Models**

for SM optimization we consider empirical models built into OSA90/hope and a fine-grid Sonnet *em* model

the HTS filter empirical model is assembled from fundamental components such as microstrip lines, coupled lines and open stubs

the  $x$ - and  $y$ -grid sizes for the numerical EM simulation are chosen as  $\Delta x = 1$  mil and  $\Delta y = 1.75$  mil

on a Sun SPARCstation 10, approximately 1 CPU hour is needed to simulate the filter at a single frequency for an on-grid point

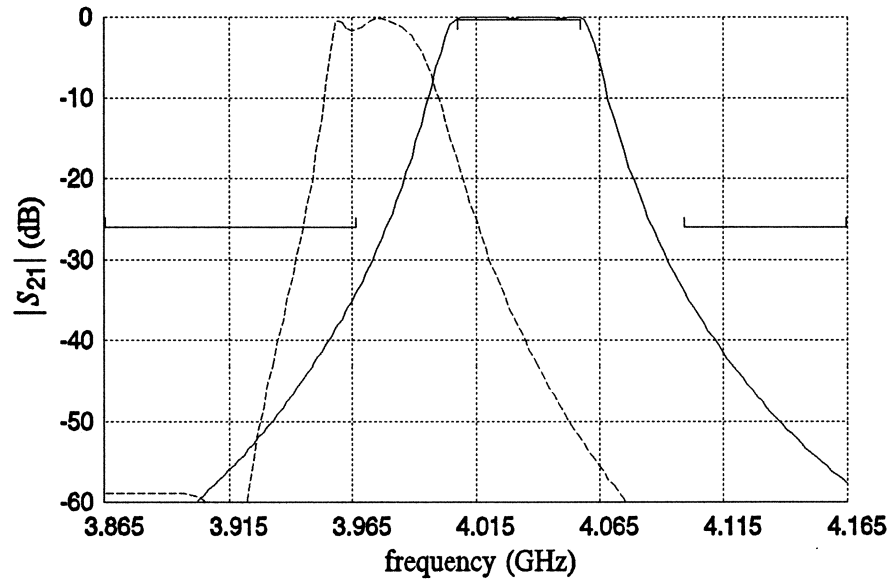
only 7 frequency points per *em* simulation are used





## HTS Filter Design with Empirical Models and the Corresponding EM Validation

OSA90/hope optimal solution (—) and *em* verification (---)



the shape of the *em* simulated response is similar to the empirical model response

the *em* response shows a significant shift of the center frequency



## HTS Filter Design Using Space Mapping

we use SM to find a solution in the EM space to substantially reproduce the performance predicted by the empirical model

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

only 4 *em* analyses were needed to obtain the new solution

only 7 frequency points per *em* simulation

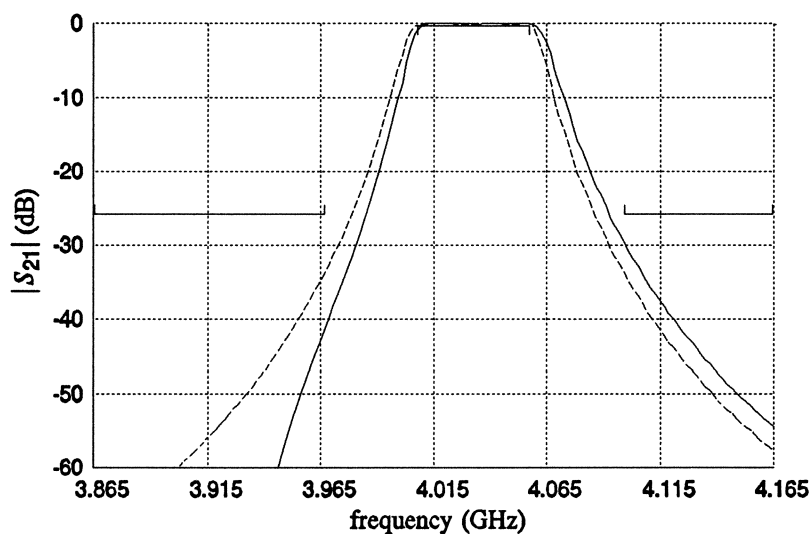
we compare the new aggressive SM result to the previous SM solution (*Bandler, Biernacki, Chen, Grobelny and Hemmers, 1994*) which was obtained after 13 *em* simulations



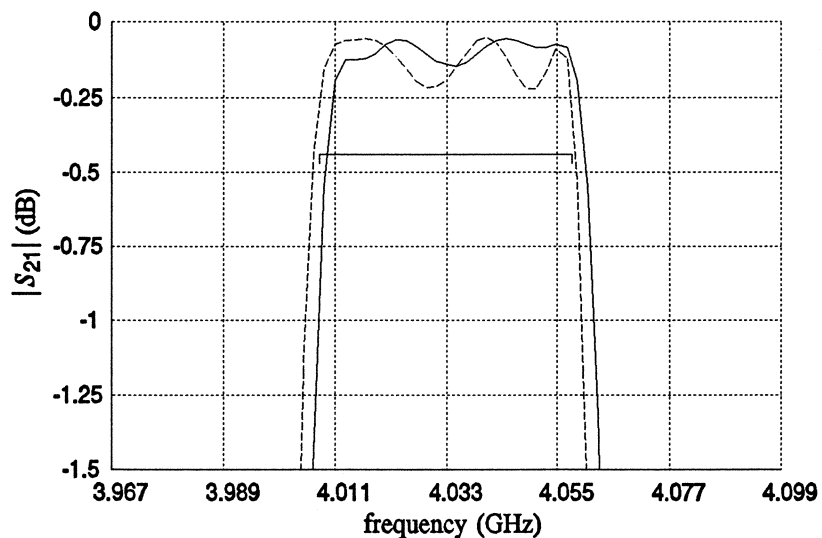
## Responses of the HTS Filter at the SM Design

OSA90/hope solution (---) and the new SM solution (—)

responses for the overall band



the passband in more detail

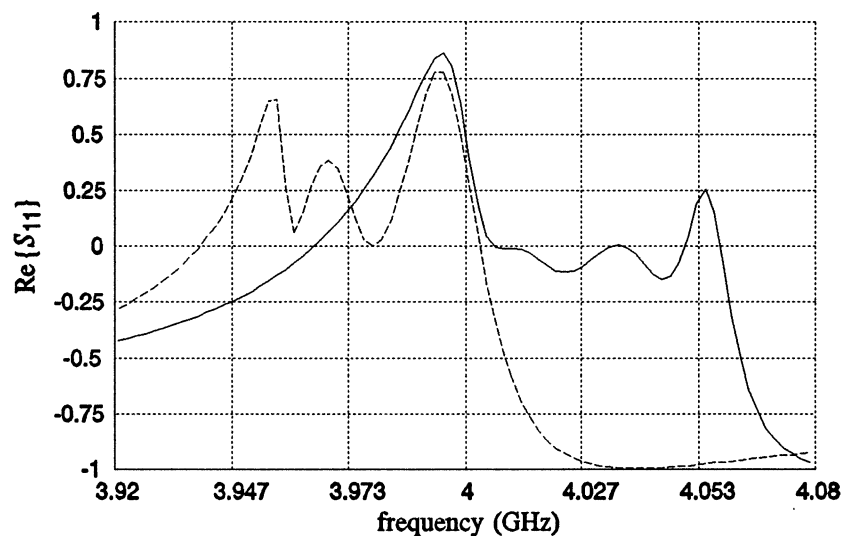




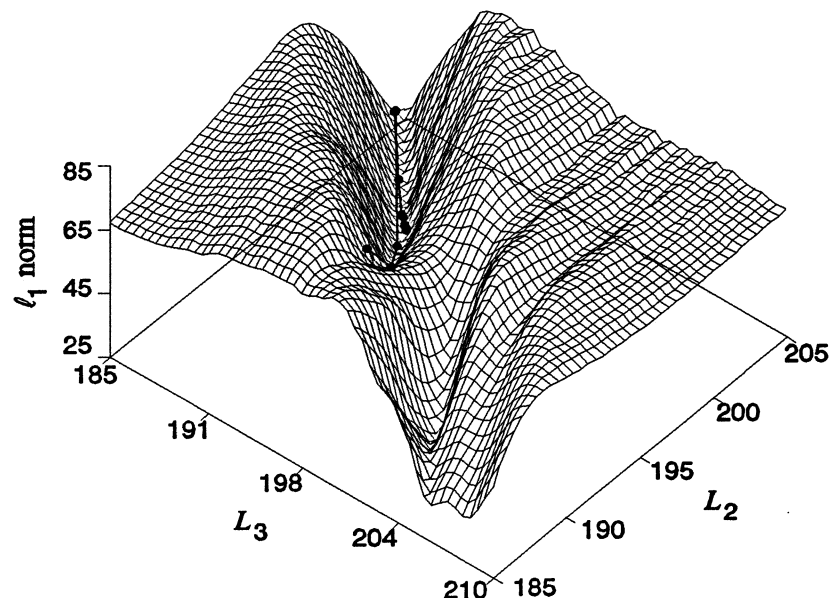
## Frequency Space Mapping for Parameter Extraction

parameter extraction can be a serious challenge, especially at the starting point, if the model responses are misaligned

$\text{Re}\{S_{11}\}$  using OSA90/hope (—) and *em* (---) at  $x_{OS}^*$



straightforward optimization from such a starting point can lead to a local minimum





## Frequency Space Mapping - Mapping and Alignment

to better condition the parameter extraction subproblem  
first, we align  $f_{OS}$  and  $f_{EM}$  along the frequency axis using

$$\omega_{OS} = T_{\omega}(\omega)$$

this frequency space mapping can be as simple as

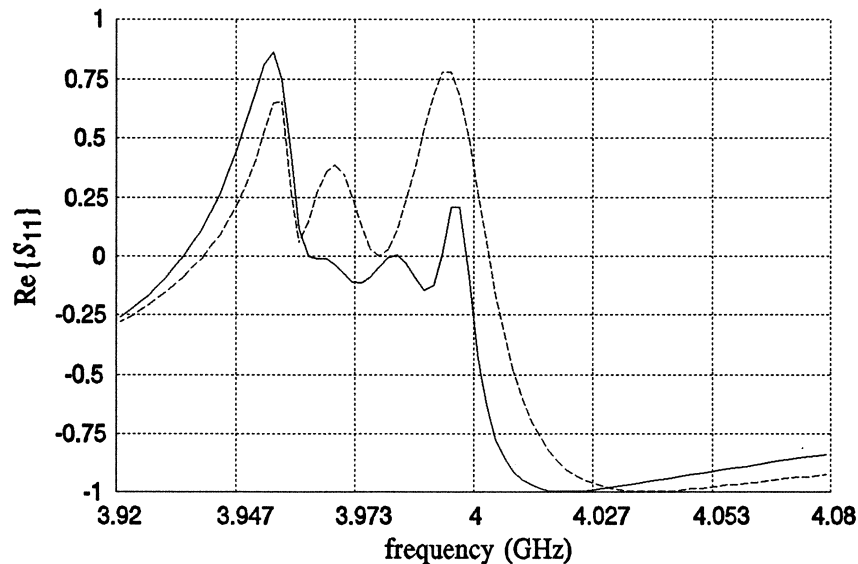
$$\omega_{OS} = S \omega + D$$

at the starting point, we determine  $S^0$  and  $D^0$  by

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

where  $x_{OS}$  and  $x_{EM}$  are fixed and  $x_{OS} = x_{EM}$

resulting alignment between the OS model (—) and *em* (---):





## **Frequency Space Mapping: Sequential FSM (SFSM) Algorithm**

we perform a sequence of optimizations to gradually achieve the identity Frequency Space Mapping

we optimize  $x_{OS}$  to match  $f_{OS}$  to  $f_{EM}$ :

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

the values  $S^i$  and  $D^i$  are updated according to

$$S^i = 1 + (S^0 - 1) \frac{(K - i)}{K}$$

and

$$D^i = D^0 \frac{(K - i)}{K},$$

respectively, for  $i = 0, 1, \dots, K$

$K$  determines the number of steps in the sequence

larger values of  $K$  increase the probability of success in the parameter extraction subproblem at the expense of longer optimization time



**Frequency Space Mapping:  
Exact Penalty Function (EPF) Algorithm**

we perform only one optimization to achieve the identity  
Frequency Space Mapping and optimize  $x_{OS}$  to match  $f_{OS}$  to  
 $f_{EM}$ :

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

from the starting point  $x_{OS} = x_{EM}$ ,

where

$$g_1 = |S - 1| \quad g_2 = |D|$$

and

$$S = S^0 \quad D = D^0$$

using  $\ell_1$ , we can obtain the *exact* solution when the factors  $\alpha_1$   
and  $\alpha_2$  are sufficiently large

in our example, the exact solution is found for  $\alpha_1 = \alpha_2 \geq 10$



## **Conclusions**

we have presented a new automated SM approach which aggressively exploits every EM analysis

we employ the Broyden update to best target each new EM point

the new method has demonstrated significant improvement over our original SM algorithm by reducing the number of EM analyses required to obtain an HTS filter design

less CPU effort is required to optimize the filter than is required by one single detailed frequency sweep

we have pioneered the application of SM to parameter extraction by developing new algorithms for overcoming difficulties caused by local minima and model misalignment

this novel concept will also have a significant impact on parameter extraction of devices





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