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OF HIGH-TEMPERATURE SUPERCONDUCTING
MICROWAVE FILTERS**

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ABSTRACT

We present novel approaches to electromagnetic design of high-temperature superconducting quarter-wave parallel coupled-line microstrip filters. The dielectric constant of substrate materials used in high-temperature superconductor technology is too large to be accurately treated by traditional microwave circuit design software packages with analytical/empirical models. We employ electromagnetic field simulation and develop a look-up table method and a powerful space mapping optimization technique, which dramatically reduce the CPU time for the design process.

INTRODUCTION

The recently discovered high-temperature superconductors (HTS) are of great potential for passive microwave military and commercial applications. Available low-loss and narrow-bandwidth (0.5 - 3%) filter banks are of very large size, which in some satellite and airborne applications is intolerable. Small conventional microstrip filters are too lossy for narrow-band applications. Using HTS technology [1, 2], however, low-loss, narrow-bandwidth microstrip filters, requiring relatively inexpensive cooling, can be made.

Advances in electromagnetic (EM) simulation provide designers the opportunity to accurately simulate passive microstrip circuits. We verified the usefulness of EM simulation in analyzing circuits built with the HTS technology by simulating two existing HTS microstrip filters. In both cases good

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correlation was observed between the EM simulated and measured responses of the filters.

In this paper we concentrate on the EM design of an HTS quarter-wave parallel coupled-line filter. The difficulty arising here is related to the large dielectric constant of the substrate materials ($\epsilon_r \approx 24$) used in the HTS technology and the inability of the traditional microwave circuit design techniques to analyze structures built of such materials. This is especially true for narrow-band, parallel coupled-line filters where loose coupling between sections is required. To overcome this problem we resort to EM field simulations. EM simulations can provide results that are in good agreement with experimental data. This, however, is at the expense of very high computational cost. This limitation shows up very clearly in analysis of narrow-bandwidth filters whose inherent high sensitivity calls for a very fine grid in the numerical EM simulation.

In order to decrease the CPU time required and overcome the high sensitivity of the filter we considered two approaches. The first approach is based on a table of coupling versus gap and frequency values and the second is based on space mapping (SM) circuit optimization. In the look-up table approach we analyze the couplings in different sections of the filter for different gaps in each of the sections swept over the frequency band of interest. The couplings are determined from EM simulations and the table is iteratively updated. In the SM approach an adaptive mapping between an OSA90/hope [3] simulation model and *em* [4, 5] simulation is established. Such a mapping, adaptively refined during optimization, allows us to benefit from the accuracy of EM simulation while using a much faster model for optimization. The SM method is a novel extension of our work on optimization-driven EM simulation [6, 7]. The method was tested using OSA90/hope interfaced to *em* through Empipe [8].

THE FILTER

We wish to design a four-pole quarter-wave parallel coupled-line microstrip filter. The geometry of the filter is shown in Fig. 1. 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 is the same for all the sections as well as for the input and output microstrip lines L_0. The thickness of the lanthanum aluminate substrate used is 20 mil and the dielectric constant is assumed to be 23.425. The design specifications are as follows.

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

$$|S_{21}| \geq 0.95 \quad \text{for} \quad 4.008 \text{ GHz} \leq f \leq 4.058 \text{ GHz}$$
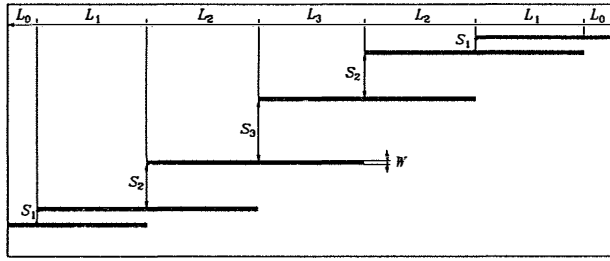
Fig. 1. The structure of the HTS quarter-wave parallel coupled-line microstrip filter (to scale). The dielectric constant and the substrate thickness are 23.425 and 20 mil, respectively. The geometrical dimensions are listed in Table I. The x and y grid sizes for *em* simulations are 1.0 and 1.75 mil. 100 elapsed minutes are needed for analysis at a single frequency on Sun SPARCstation 10.

This corresponds to a 1.25% bandwidth. L_1, L_2, L_3, S_1, S_2 and S_3 are the design parameters. L_0 and W are fixed.

FILTER DESIGN USING TRADITIONAL SIMULATORS

We started the design process by optimizing the filter using two commercial microwave CAD packages, namely, OSA90/hope and Touchstone [9]. The solutions are listed in the first two columns of Table I. Subsequently we performed *em* simulations at both solutions. The *em* simulation results differed from the circuit simulation results and did not satisfy the specifications. The responses are shown in Fig. 2. We set out to develop methods for adapting the traditional analytical/empirical models for the design process.

FILTER DESIGN USING THE LOOK-UP TABLE METHOD

Although the technique is general in nature, it has been applied only to the class of filters known as parallel coupled-line filters which are derivable from lowpass ladder networks. One starts with the normalized lowpass ladder network elements which satisfy some predetermined shape requirement and results in the lowpass prototype element values also known as the g values. An appropriate bandpass and impedance transformation is performed which leads to good approximations of the even and

TABLE I
HTS PARALLEL COUPLED-LINE MICROSTRIP FILTER DESIGN RESULTS

| Parameter (mil)	OSA90/hope Optimization	Touchstone Optimization	Look-up Table Method	SM Method
L_1	191.00	188.70	188.70	190.00
S_1	21.74	22.52	20.88	19.25
L_2	195.58	188.11	188.10	192.00
S_2	96.00	93.19	76.02	75.25
L_3	191.00	188.58	188.59	189.00
S_3	114.68	109.13	85.07	91.00
W	7.00	6.93	6.93	7.00
L_0	50.00	50.00	50.00	50.00
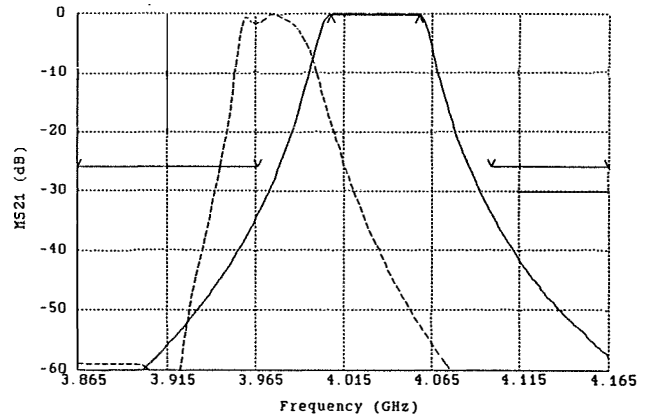
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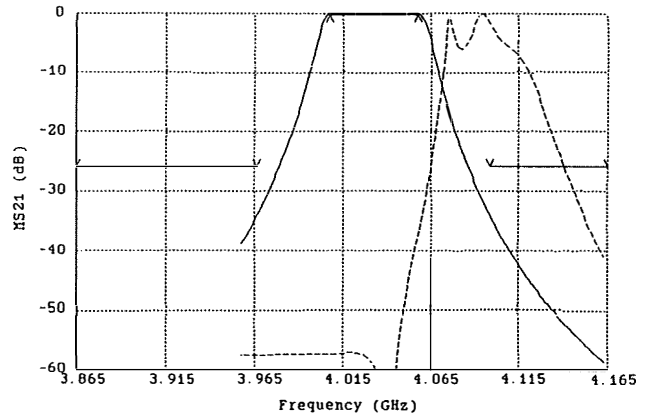
(b)

Fig. 2. The optimal solutions (solid lines) of $|S_{21}|$ obtained using (a) OSA90/hope and (b) Touchstone. The corresponding *em* simulation results are shown as dashed lines. V indicate upper and Λ indicate lower specifications.

odd mode impedances of the coupled-line sections which comprise the filter. The next step in the design process is to determine the geometry or conductor arrangement which realizes this set of even/odd mode impedances. The medium that we have chosen is microstrip on 20 mil lanthanum aluminate. In this medium, the coupled sections are characterized by three geometric parameters; line width, coupling length and coupling gap, which must be chosen to provide the required even and odd mode impedances. The ratio of these impedances depends only on the coupling coefficient of the coupler and the product depends on the impedance level.

The simulator aided design process consists of estimating the quarter wavelength in the medium at filter band center, and the gap required for the coupling. One then constructs a model for the field simulator which consists of a coupled-line with input and output ports on a diagonal with the other diagonal remaining as open circuits. Actually, several models are constructed over a range of gaps so that one can interpolate the *em* simulator's results to the required gap based upon the required coupling factor. This process is repeated for each coupled section of the filter. When a complete set of gaps has been determined by interpolation, the filter is modeled for analysis by the field simulator. The result usually has a shape that is close to the desired shape but is offset in center frequency. The amount of the frequency error and the original

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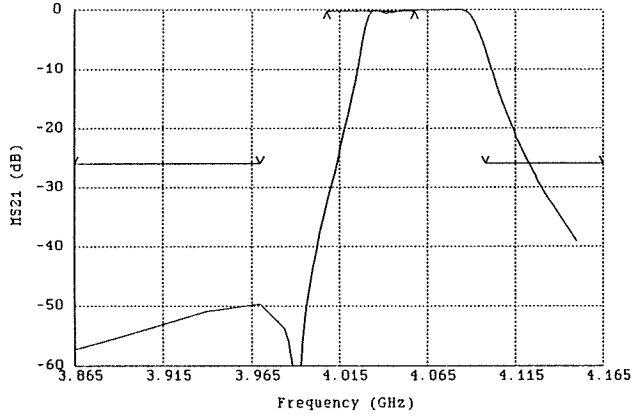
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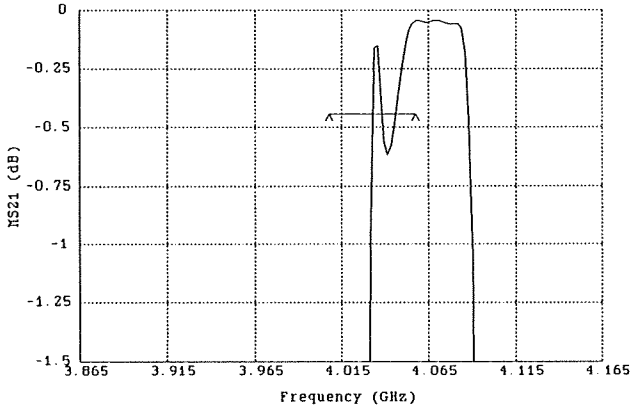
(b)

Fig. 3. The *em* simulated $|S_{21}|$ response of the HTS parallel coupled-line filter at the solution obtained using the look-up table method. (a) Response for the overall band. (b) Passband details of the response. $\vee$ and $\wedge$ indicate upper and lower specifications, respectively. The response exhibits the desired shape with slightly shifted center frequency.
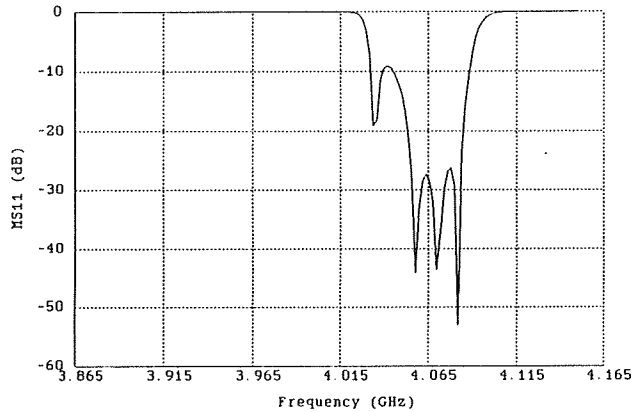

Fig. 4. The *em* simulated $|S_{11}|$ response of the HTS parallel coupled-line filter at the solution obtained using the look-up table method.

coupling length provide enough information to compute a length correction, i.e., the fractional change in frequency is proportional to the negative of the fractional change in length.

The process is then repeated using the new coupling length. We have found adequate convergence after three iterations.

The filter's $|S_{21}|$ and $|S_{11}|$ responses simulated by *em* at the look-up table method solution are shown in Figs. 3 and 4, respectively. The solution point is listed in the third column of Table 1. The $|S_{21}|$ response has the desired shape but the center frequency is slightly shifted w.r.t. specifications. Also, a small ripple present in the passband, see Fig. 3(b), results in non-uniform $|S_{11}|$ in the passband.

FILTER DESIGN USING THE SPACE MAPPING METHOD

In the novel SM optimization technique we create and iteratively refine a mapping

$$x_{OS} = T(x_{EM}) \qquad (1)$$

from the EM simulator input space $\{x_{EM}\}$ onto the optimization system (OS) parameter space $\{x_{OS}\}$. Though not necessary, it is desirable that T is invertible. If so, the inverse mapping T^{-1} is used to find the image of the optimal OS solution x_{OS}^*, namely,

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

T is established through an iterative process. The initial mapping $T^{(0)}$ is found using a preselected set B_{EM} of k points in the EM input space and the set B_{OS} of corresponding points in the OS parameter space. The points in B_{OS} are determined such that

$$f_{OS}(x_{OS}^i) \approx f_{EM}(x_{EM}^i), \quad i = 1, 2, ..., k \qquad (3)$$

where f_{OS} and f_{EM} are the circuit responses simulated by the OS and EM simulators, respectively. At the jth iteration B_{EM} is expanded by the new image of x_{OS}^* computed using $(T^{(j)})^{-1}$ and B_{OS} is expanded accordingly. The iterations continue until

$$f_{EM}(\bar{x}_{EM}) \approx f_{OS}(x_{OS}^*) \qquad (4)$$

Applying the SM optimization technique to the design of our HTS filter we used the Empipe [8] interface interconnecting *em* to OSA90/hope. All the processing needed to establish the mapping was performed within the OSA90/hope environment.

A total of 13 *em* simulations was sufficient to establish the mapping T which satisfies (4). The point $\bar{x}_{EM}$ obtained as the $(T)^{-1}$ image of x_{OS}^* and listed in the fourth column of Table I gave us an excellent response of the filter, as simulated by *em*. The $|S_{21}|$ response, shown in Fig. 5, meets the design specifications well. The $|S_{11}|$ response, shown in Fig. 6, is also improved.

CONCLUSIONS

We have presented EM-based methods for CAD of narrow-band parallel coupled-line microstrip filters built using the HTS technology. The new space mapping optimization method is a general approach which can be applied to other design problems. It is especially attractive for designs involving CPU intensive simulators, where it substantially decreases the number of necessary simulations. Filters will be built according to the results obtained from both methods.

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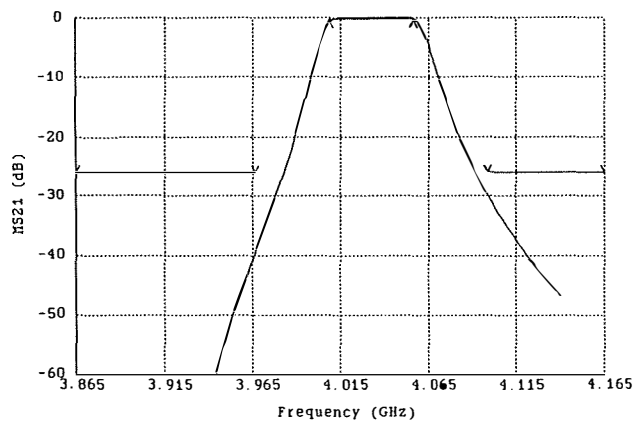
(a)
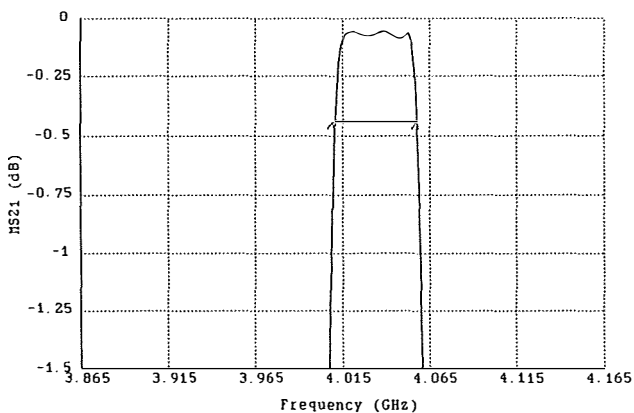
(b)

Fig. 5. The *em* simulated $|S_{21}|$ response of the HTS parallel coupled-line filter at the solution obtained using the SM optimization method. (a) Response for the overall band. (b) Passband details of the response. V and Λ indicate upper and lower specifications, respectively.
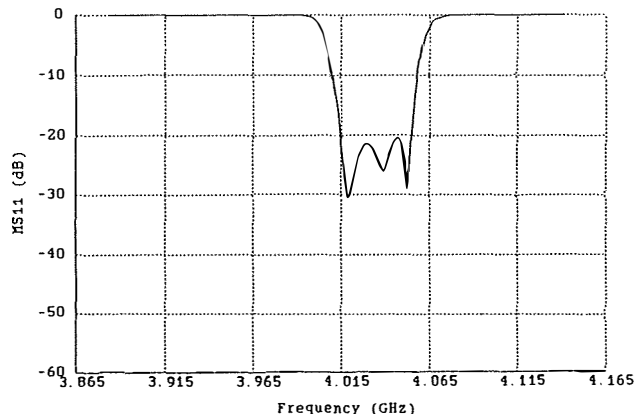

Fig. 6. The *em* simulated $|S_{11}|$ response of the HTS parallel coupled-line filter at the solution obtained using the SM optimization method.

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