EM-Based Design of Large-Scale Dielectric-Resonator Filters and Multiplexers by Space Mapping

Mostafa A. Ismail, *Member, IEEE*, David Smith, Antonio Panariello, Ying Wang, and Ming Yu, *Senior Member, IEEE*

***Abstract*—A novel design methodology for filter and multiplexer design is presented. For the first time, finite-element electromagnetic (EM)-based simulators and space-mapping optimization are combined to produce an accurate design for manifold-coupled output multiplexers with dielectric resonator (DR) loaded filters. Finite-element EM-based simulators are used as a fine model of each multiplexer channel, and a coupling matrix representation is used as a coarse model. Fine details such as tuning screws are included in the fine model. The DR filter and multiplexer design parameters are kept bounded during optimization. The sparsity of the mapping between the design parameters and the coupling elements has been exploited. Our approach has been used to design large-scale output multiplexers and it has significantly reduced the overall tuning time compared to traditional techniques. The technique is illustrated through design of a five-pole DR filter and a ten-channel output multiplexer.**

***Index Terms*—Dielectric-resonator (DR) filters, electromagnetic (EM) optimization, filter design, multiplexer design, space mapping.**

I. Introduction

THE motivation of this study originated from designing output multiplexers with dielectric-resonator (DR) filter channels. Accurate multiplexer geometrical dimensions are required in order to minimize the tuning time of every channel and, hence, the over all tuning time of the multiplexer. Three-dimensional (3-D) finite-element-based electromagnetic (EM) simulators can accurately model general waveguide filters and can model (if used carefully) fine details such as tuning screws and probes. On the other hand, they are very computer intensive, which makes them impractical to use in direct optimization of large-scale circuits such as manifold-coupled multiplexers. As will be seen in this paper, combining these simulators with space-mapping optimization [1]–[4] provides an efficient design methodology for DR filters and multiplexers.

Filter design exploiting coupling matrix representation and full-wave EM simulators has been considered by several authors [5]–[9]. In [5], filter geometrical parameters are correlated to corresponding coupling elements by evaluating the sensitivity information at every iteration. Sensitivity evaluation by commercial EM simulators is very costly, particularly in the case of multiplexer design where we have many channels (very large number of parameters). Issues such as robustness against divergence and exploiting sparsity information have not been addressed. Extension to DR filter or multiplexer design has also not been considered. A hybrid circuit full-wave approach is presented in [10] to design manifold-coupled multiplexers without tuning elements. Full-wave optimization of the entire multiplexer structure (the multiplexer considered in [10] can be analyzed by the mode-matching technique) is performed in the final step. In case of DR manifold-coupled multiplexer design, it is impractical to perform full-wave optimization of the entire structure.

In this paper, we will demonstrate the full power of space mapping in solving large-scale filter and multiplexer problems. The filter parameters are kept bounded during space-mapping optimization. From practical experience, we notice that the mapping between the coupling elements and the filter parameters is sparse and this has been exploited in the design process. Coupling matrix representation of narrow bandpass filters [11] is used as a coarse model of each filter channel of the multiplexer. Full-wave EM simulators are considered as the fine model. The multiplexer model comprises a number of filters (channels) connected to a manifold through waveguide T-junctions. The T-junctions are analyzed by the mode-matching technique and the manifold is modeled by a single-mode waveguide transmission line.

The multiplexer design procedure we propose follows a hybrid EM circuit optimization approach. It starts by optimizing the manifold electrical parameters, as well as the coupling elements of all channels to achieve the required specifications. Space-mapping optimization is then applied to every channel to evaluate the optimal channel parameters. Finally, a more accurate multiplexer model is obtained by replacing the circuit model of each channel with the corresponding EM s-parameters sweep (at the optimal channel parameters) over the multiplexer frequency band. The new multiplexer model then includes channel dispersion and spurious modes. To account for the effects of dispersion and spurious modes, the new multiplexer model is optimized (with respect to the manifold geometrical dimensions) to achieve the required specifications.

II. Basic Concepts

A. Channel Models

Each channel of the multiplexer is a narrow bandpass filter. The equivalent circuit of this filter [11] is shown in Fig. 1,

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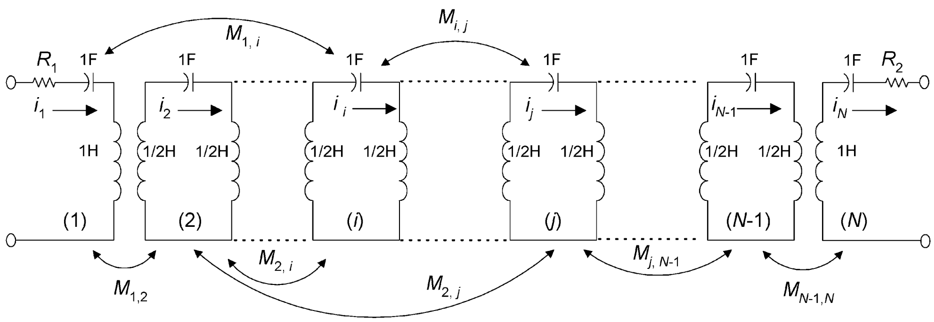

Fig. 1. Equivalent circuit of an N-coupled resonator filter.

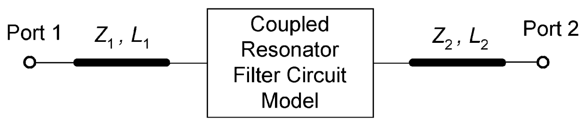

Fig. 2. Coarse model of a multiplexer channel.

where N is the filter order, $M_{i,j}$ represents the coupling between resonators i and j, respectively, and R_1 and R_2 represent the input/output coupling. The scattering parameters of this circuit model are related to the coupling matrix $\boldsymbol{M} = [M_{i,j}]$, $i = 1, \ldots, N$ and $j = 1, \ldots, N$ by [12]

$$S_{21} = -2j\sqrt{R_1R_2}\left[(\lambda\boldsymbol{I} - j\boldsymbol{R} + \boldsymbol{M})^{-1}\right]_{N,1} \quad (1a)$$

$$S_{11} = 1 + 2jR_1\left[(\lambda\boldsymbol{I} - j\boldsymbol{R} + \boldsymbol{M})^{-1}\right]_{1,1} \quad (1b)$$

where λ is related to the center frequency ω_0 and the bandwidth $\Delta\omega$ by $\lambda = \omega_0/\Delta\omega(\omega/\omega_0 - \omega_0/\omega)$, $\boldsymbol{I}$ is the identity matrix and $\boldsymbol{R}$ is a matrix of zero entries, except for the elements $(1,1)$ and (N,N), which take the value of R_1 and R_2, respectively. The channel coarse model is represented by the network model in Fig. 1 in addition to two input/output transmission lines for reference plane adjustment (see Fig. 2). The parameters L_1, Z_1, L_2, and Z_2 are the lengths and characteristic impedances of the input and output transmission lines, respectively. Ansoft HFSS[1] is used as a fine model of the filter channel.

The coupling matrix that satisfies some required specifications is referred to as the ideal coupling matrix. It corresponds to the optimal coarse model solution in space-mapping terminology [1]. There exists a mapping between the coupling matrix elements and channel geometrical parameters. This naturally leads to the use of space-mapping optimization to evaluate the channel design parameters that correspond to the ideal coupling matrix.

B. Multiplexer Model

The multiplexer we consider in this study is a manifold-coupled output multiplexer (see Fig. 3). It comprises a number of narrow bandpass filters (channels) connected to a waveguide manifold. The symbol "T-J" denotes either an H- or E-plane waveguide T-junction and "C" denotes a circuit model of a waveguide transmission line. In our design procedure, the T-junctions are analyzed by an exact mode-matching technique. Each channel is either represented by its coarse model (see Fig. 2) or by the s-parameters block obtained from the EM simulator. The design procedure in Section IV will make use of both representations to get the optimal geometrical dimensions of all the channels and manifold.

[1]Ansoft HFSS, ver. 8.0.25, Ansoft Corporation, Pittsburgh, PA, 2001.

III. Bandpass Filter Channel Design

As we will see here, the channel design problem fits in the space-mapping framework [1]. We follow the trust-region aggressive space-mapping algorithm in [4] with some key modifications. In the optimization-step computation, we impose lower and upper bound constraints on the channel design parameters. These bounds reflect geometrical constraints imposed on the channel parameters. The mapping between the channel geometrical dimensions and the coupling elements is sparse and this has been taken into account.

A. Problem Formulation

Let the vector $\boldsymbol{d}$ of dimension n represent the channel geometrical dimensions. Let the vector $\boldsymbol{m}$ of dimension m contain all the coupling elements including input/output couplings. We assume that for a channel with a design parameter vector $\boldsymbol{d}$ there exists a unique coupling vector $\boldsymbol{m}$ such that the s-parameters of the coarse model in Fig. 2 match those obtained by the EM simulator. There exists a mapping between the vectors $\boldsymbol{m}$ and $\boldsymbol{d}$ as follows:

$$\boldsymbol{m} = \boldsymbol{p}(\boldsymbol{d}). \quad (2)$$

The objective is to find the optimal design parameters $\boldsymbol{d}^*$ corresponding to an ideal coupling vector $\boldsymbol{m}^*$. This can be evaluated by solving the nonlinear system of equations

$$\boldsymbol{p}(\boldsymbol{d}) - \boldsymbol{m}^* = 0. \quad (3)$$

As in [1], this nonlinear system of equations is solved iteratively using linear approximation of the mapping in (2). The linear mapping at the ith iteration is given by

$$\boldsymbol{m} - \boldsymbol{m}_i = \boldsymbol{J}_i(\boldsymbol{d} - \boldsymbol{d}_i) \quad (4)$$

where $\boldsymbol{J}_i$ is an $m \times n$ matrix representing the Jacobian of $\boldsymbol{p}(\boldsymbol{d})$ at the ith iteration. The initial value of the Jacobian $\boldsymbol{J}_0$ is approximated by finite difference around the initial design parameters. The Broyden formula [2] is used to update $\boldsymbol{J}_i$.

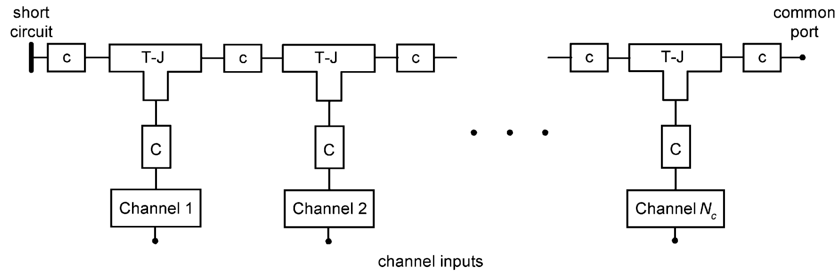

Fig. 3. N_c-channel manifold-coupled output multiplexer.

B. Optimization-Step Computation

The optimization-step computation is modified from the one in [4] to include upper and lower bounds on the design parameters. The residual $\boldsymbol{r}$ is defined by

$$\boldsymbol{r}(\boldsymbol{d}) = \boldsymbol{p}(\boldsymbol{d}) - \boldsymbol{m}^*. \tag{5}$$

At the ith iteration, the residual $\boldsymbol{r}(\boldsymbol{d}_i + \boldsymbol{s})$, where $\boldsymbol{s}$ is the optimization step, is approximated by the first two terms of Taylor series

$$\boldsymbol{r}(\boldsymbol{d}_i + \boldsymbol{s}) \approx \boldsymbol{r}_i + \boldsymbol{J}_i\boldsymbol{s} \tag{6}$$

where $\boldsymbol{r}_i = \boldsymbol{r}(\boldsymbol{d}_i)$. The optimization step $\boldsymbol{s}$ is obtained by minimizing the $l2$-norm of the residual (6) subject to bounds on the design parameters and a trust region on the step $\boldsymbol{s}$

$$\boldsymbol{s} = \arg\min_{s} \frac{1}{2} \|\boldsymbol{r}_i + \boldsymbol{J}_i\boldsymbol{s}\|_2^2$$

subject to

$$\begin{aligned} \|\boldsymbol{s}\|_\infty &\leq \Delta_i \\ \boldsymbol{l} &\leq \boldsymbol{d}_i + \boldsymbol{s} \leq \boldsymbol{u} \end{aligned} \tag{7}$$

where $\boldsymbol{l}$ and $\boldsymbol{u}$ are vectors of lower and upper bounds, respectively, and Δ_i is the size of the trust region at the ith iteration. The trust region in (7) is defined in terms of the infinity norm because, this way, it is easier to solve (7) than if the Euclidean norm is used (global convergence of trust-region methods does not depend on the kind of the norm used [13]). Therefore, the trust-region constraint in (7) can be replaced by [13]

$$-\Delta_i\boldsymbol{e} \leq \boldsymbol{s} \leq \Delta_i\boldsymbol{e} \tag{8}$$

where $\boldsymbol{e}$ is a vector of all. Replacing the trust-region constraint in (7) with (8) leads to a quadratic optimization problem with simple bound constraints. This problem can be solved efficiently by the gradient-projection method in [13]. As in [4], the solution $(\boldsymbol{d}_i + \boldsymbol{s})$ is accepted only if it results in a reduction in the residual $\boldsymbol{r}$. The trust region is also updated according to the criteria in [4].

C. Sparsity of the Matrix $\boldsymbol{J}$

In waveguide filters, changing one geometrical parameter affects only some specific coupling values and has little effect on the other couplings. This observation indicates that the mapping $\boldsymbol{p}$ in (2) is sparse (hence, the Jacobian $\boldsymbol{J}$ in (4) is also sparse). We incorporate this observation in our technique by keeping the matrix $\boldsymbol{J}$ sparse during Broyden update [3]. The sparsity features can be deduced from the following practical observations.

1) Changing the input/output irises (or probes) affects only the input/output couplings and the resonant frequency of the nearest resonators.
2) Changing the parameters of a resonator results only in changing the resonant frequency of this resonator.
3) Changing an iris (or a probe) between two cavities results in changing the coupling between the cavities and the resonant frequencies of the two cavities.

D. Parameter Extraction

The parameter-extraction problem in our case is to get a coupling vector $\boldsymbol{m}$ such that the s-parameters of the model in Fig. 2 match those obtained by the EM simulator (in our case, Ansoft HFSS) at the design parameters vector $\boldsymbol{d}$. Most of the techniques in literature use optimization to extract $\boldsymbol{m}$ [5], [14]. Most recently, an analytical technique was developed in [15] to extract the coupling elements of symmetric coupled resonator filters. In our case, we cannot use this technique since the filters we consider are nonsymmetrical. We use nonlinear least square optimization to extract the coupling vector $\boldsymbol{m}$.

IV. Manifold-Coupled Multiplexer Design

Assume that the multiplexer has N_c channels (see Fig. 3). The design procedure to evaluate the manifold and the channels geometrical dimensions are as follows.

Step 1) Optimize the overall circuit model of the multiplexer (manifold parameters and coupling elements of all channels) to meet the required specifications. The resulting coupling values are denoted as ideal couplings.

Step 2) For $i = 1, 2, \ldots, N_c$, apply the technique in Section III to evaluate the optimal design parameters of the ith channel.

Comment: The starting point for the $(i+1)$th channel can be obtained by extrapolating the mapping information of the ith channel.

Step 3) Get a more accurate model of the multiplexer by replacing the coarse model (coupling matrix) of each channel with the corresponding s-parameters sweep block (computed by the EM simulator at the optimal channel design parameters over the multiplexer frequency band of interest). Notice that the resulting

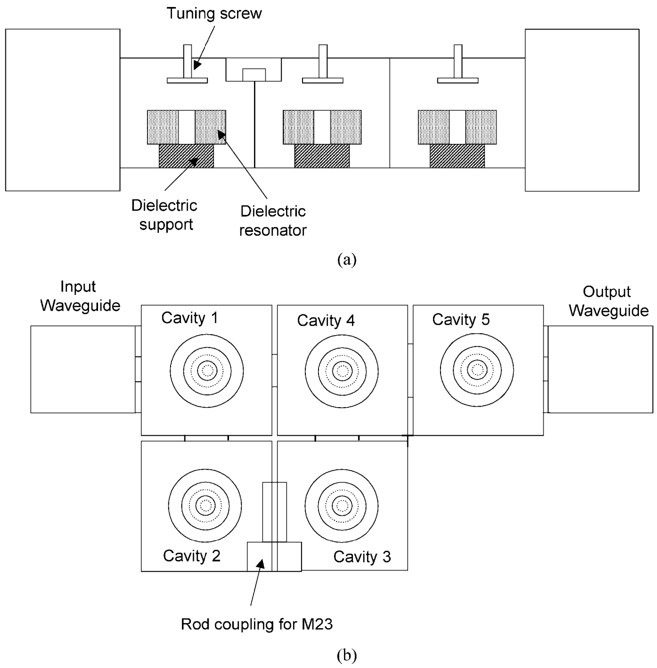

Fig. 4. Five-pole DR filter structure. (a) Side view. (b) Top view.

multiplexer model takes into account the effects of channel dispersion and spurious modes.

Step 4) Evaluate the manifold parameters by optimizing the new multiplexer model to meet the required specifications. The optimization variables at this stage are the manifold spacing between channels and the lengths of the waveguides connecting the channels to the manifold.

Comment: Notice that by optimizing the new multiplexer model obtained in Step 3), we adjust the manifold parameters to compensate for channel dispersion and spurious modes.

When designing a channel using the space-mapping technique, a number of EM simulations is needed in order to get an initial approximation for the Jacobian $\boldsymbol{J}_0$ in (6). From practical experience, we notice that the same Jacobian value can be used for adjacent channels as long as they have comparable normalized coupling values and bandwidth. Hence, the overall number of EM simulations is significantly reduced.

V. EXAMPLES

A. Double-Terminated Five-Pole DR Filter

We consider the five-pole DR filter in Fig. 4. The filter center frequency and bandwidth are 3.4 GHz and 54 MHz (1.6%), respectively. The number of coupling elements is 12 and the number of design parameters is also 12. Each design parameter corresponds to a coupling element. The input/output waveguides are coupled to the first and fifth resonators, respectively, through double-ridged irises. All couplings are realized by rectangular irises, except the coupling M23, which is realized by a rod coupling [16] for power-handling consideration. Tuning screws are added to a nominal depth to maximize the tuning

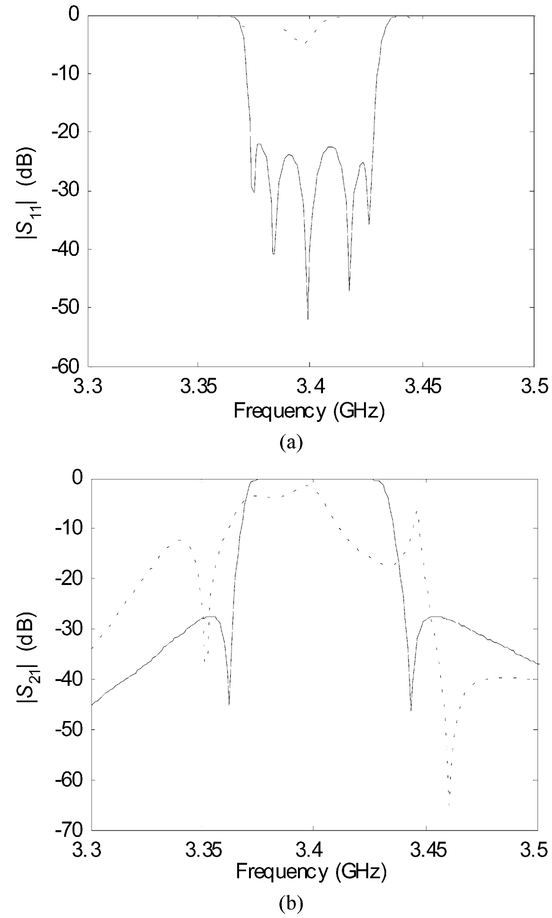

Fig. 5. Ideal responses (solid line) versus the EM responses (dotted line) by Ansoft HFSS at the initial filter parameters. (a) $|S_{11}|$ (in decibels). (b) $|S_{21}|$ (in decibels).

range. The ideal normalized input/output resistances and coupling matrix are given by

$$R_1 = R_2 = 1.133$$
$$\boldsymbol{M} = \begin{bmatrix} 0 & 0.866 & 0 & -0.252 & 0 \\ 0.866 & 0 & 0.792 & 0 & 0 \\ 0 & 0.792 & 0 & 0.595 & 0 \\ -0.252 & 0 & 0.595 & 0 & 0.901 \\ 0 & 0 & 0 & 0.901 & 0 \end{bmatrix}.$$

The filter is analyzed by Ansoft HFSS (fine model). The coarse model is analyzed by a program developed at Com Dev International, Cambridge, ON, Canada, which takes into consideration dispersion, as well as loss effects. It also has some optimization capability and it has been used to extract the coupling values corresponding to a specific target s-parameters. The ideal responses and the fine model responses at the initial design parameters are shown in Fig. 5. The error between the ideal couplings and extracted couplings of the initial fine model response (based on $l2$-norm) is 3.05. To compute the initial Jacobian J_0 in (6), we performed seven Ansoft HFSS simulations around the initial design parameters: one simulation for the sensitivity of the input/output couplings (they have similar sensitivities), one simulation for the sensitivity of the resonators, and five simulations

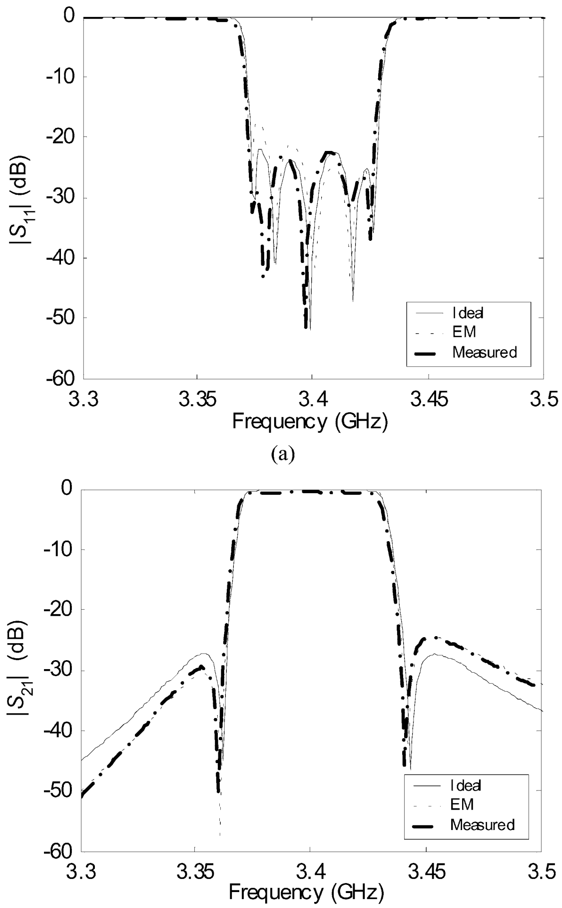

Fig. 6. Comparison between ideal responses, HFSS responses at the optimal filter parameters, and measured responses. (a) $|S_{11}|$ (in decibels). (b) $|S_{21}|$ (in decibels).

for the sensitivities of the remaining couplings. The results in Fig. 6 are obtained after ten iterations. The extracted couplings corresponding to this solution is given by

$$R_1 = 1.123$$
$$R_2 = 1.141$$
$$\boldsymbol{M} = \begin{bmatrix} 0 & 0.850 & 0 & -0.248 & 0 \\ 0.850 & 0.009 & 0.803 & 0 & 0 \\ 0 & 0.803 & 0.01 & 0.596 & 0 \\ -0.248 & 0 & 0.596 & 0.005 & 0.885 \\ 0 & 0 & 0 & 0.885 & 0.015 \end{bmatrix}.$$

The filter was built, easily tuned, and measured. Comparison between ideal, EM (Ansoft HFSS), and measured responses are shown in Fig. 6.

B. Ten-Channel Output Multiplexer

To illustrate the multiplexer design procedure, we consider a ten-channel manifold-coupled output multiplexer in the frequency band of 3.5–4.25 GHz. Eight channels have a bandwidth of 1.5% and the remaining two have a bandwidth of 0.8%. Every channel is a five-pole DR filter, as shown in Fig. 4. Ansoft HFSS is used as a fine model of every channel, and the network model

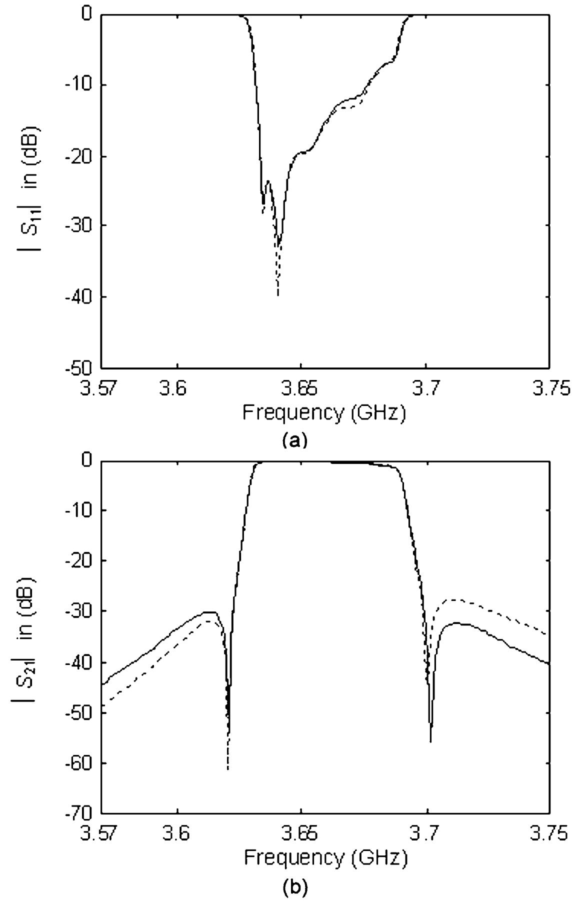

Fig. 7. Responses of the first channel of the ten-channel output multiplexer (the solid line is the ideal response and the dotted line is the EM response at the optimal design parameters). (a) $|S_{11}|$ (in decibels). (b) $|S_{21}|$ (in decibels).

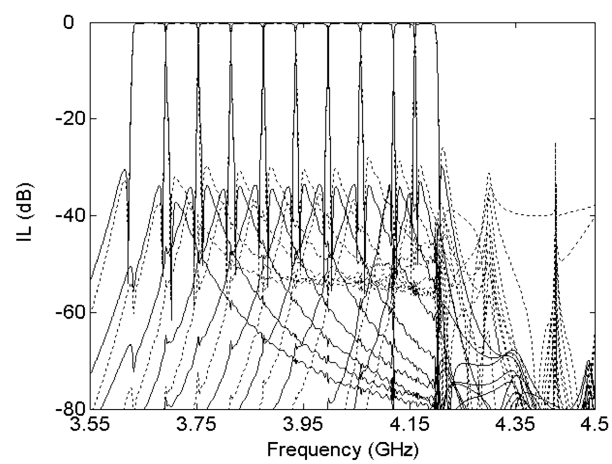

Fig. 8. Ideal response of the ten-channel DR multiplexer prototype (solid line) versus the EM response (dotted line).

in Fig. 2 is used as a coarse model. The T-junctions connecting the channels to the manifold are analyzed by mode matching.

Ideal channel coupling values are obtained in the first step of the design procedure in Section IV. Space-mapping optimization (Section III) is then applied to each channel to get the optimal channel dimensions. For example, the results of applying space-mapping optimization to the first channel are shown in Fig. 7 (seven iterations are required). An accurate multiplexer

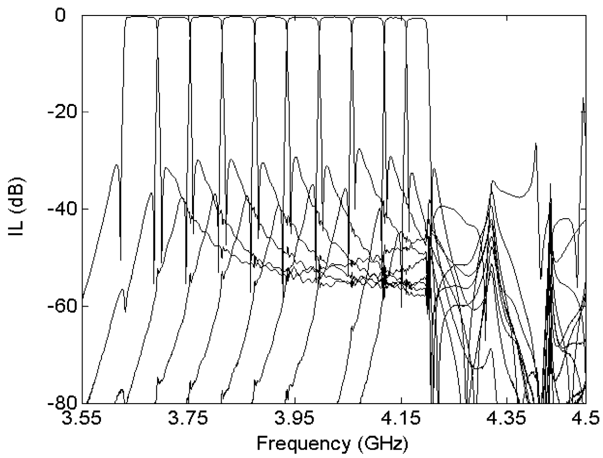

Fig. 9. Measured response of the ten-channel DR multiplexer.

model is obtained by replacing each channel with the corresponding s-parameters sweep obtained by HFSS at the optimal channel dimensions. As a result, the new multiplexer model includes channel dispersion and spurious modes. Finally, the manifold parameters are reoptimized to meet the required specifications. Fig. 8 compares between the multiplexer ideal response and the EM response where every channel is replaced by its simulated s-parameters (by Ansoft HFSS). The measured response of the multiplexer is shown in Fig. 9. The spurious modes predicted by EM analysis in Fig. 8 correlate very well with the measurements in Fig. 9.

VI. Conclusions

A new design methodology for DR filters and multiplexers has been presented. The technique is readily applicable to other types of filters and multiplexers. Space-mapping optimization has been used to design the multiplexer channels. Finite-element EM-based simulators are used as a fine model of each multiplexer channel and coupling matrix representation is used as a coarse model. Fine details such as tuning screws are included in the design process. Our design procedure takes into account the effects of dispersion and spurious modes. It results in accurate design of DR filters and multiplexers. As a result, the overall tuning time is significantly reduced. The technique is demonstrated through design of a five-pole DR filter and a ten-channel manifold-coupled output multiplexer.

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