# EM Based Design Of Large-Scale Dielectric Resonator Multiplexers By Space Mapping

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*Abstract* — **A novel design methodology for multiplexer design is presented. For the first time, finite element 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. Therefore channel dispersion and spurious modes are taken into account. The DR filter channel design parameters are kept bounded during optimization. Our approach has been used to design large-scale manifold coupled output multiplexers and it has significantly reduced the overall tuning time compared to traditional techniques. The technique is illustrated through design of a 10-channel output multiplexer with 5-pole DR filter based channels.**

## I. Introduction

In this work, we exploit space-mapping optimization technique [1] and [2] to design large-scale manifold coupled output multiplexers. In DR output multiplexer design, accurate geometrical dimensions are required in order to minimize the tuning time of every channel and hence the overall tuning time of the multiplexer. Finite element EM simulators can analyze general waveguide structures and can model (if used carefully) fine details such as tuning screws and probes. For this reason they are used as a fine model of each multiplexer channel. Coupling matrix representation of narrow bandpass filters [3] is used as a coarse model. The channel parameters are kept bounded during space mapping optimization. The sparsity of the mapping between the design parameters and the coupling elements has been exploited.

Several authors [4]–[6] have utilized coupling matrix representation and full wave EM simulators for filter design. Extension to DR filter or multiplexer design has not been considered. A hybrid circuit-full-wave approach is presented in [7] to design manifold multiplexers without tuning elements. Full wave optimization of the entire multiplexer structure is performed in the final step. This was feasible since the multiplexer considered can be analyzed by mode matching technique. In case of DR manifold multiplexer design, it is impractical to perform full wave optimization of the entire multiplexer structure.

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. Then space-mapping optimization is applied to every channel to evaluate the optimal channel dimensions. 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 dimensions) over the multiplexer frequency band. The new multiplexer model then includes channel dispersion and spurious modes. To account for the effect of dispersion and spurious modes the new multiplexer model is optimized (with respect to the manifold dimensions) to achieve the required specifications.

## II. Basic Concepts

### *A. Channel Models*

The coarse model of each multiplexer channel consists of a network model of a narrow bandpass coupled resonator filter [3] (coupling matrix representation) in addition to two input/output transmission lines for reference plane adjustment (see Fig. 1). The parameters $L_1$, $Z_1$, $L_2$, $Z_2$ are the lengths and the characteristic impedances of the input and output transmission lines, respectively. Ansoft HFSS [8] 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 coupling matrix elements and channel geometrical parameters. This leads naturally to the use of space mapping optimization to evaluate the channel dimensions that correspond to the ideal coupling matrix.



 

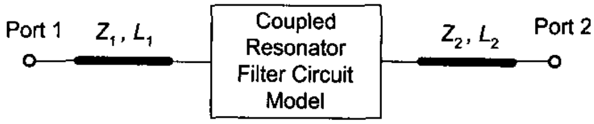


Fig. 1. The coarse model of a multiplexer channel.

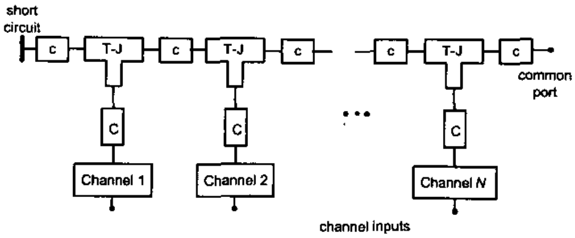


Fig. 2. $N$-channel manifold-coupled output multiplexer.

*B. Multiplexer Model*

The multiplexer considered in this work is a manifold-coupled output multiplexer (see Fig. 2). It comprises a number of narrow bandpass filters (channels) connected to a waveguide manifold. The symbol "T-J" denotes either an H-plane 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 exact mode matching technique. Each channel is either represented by its coarse model (Fig. 1) or by the s-parameters block obtained from the EM simulator. The algorithm presented in Section IV will make use of both representation to get the optimal physical dimensions of all the channels and the manifold.

## III. Bandpass Filter Channel Design

The channel design procedure follows the algorithm in [2] 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 on the channel parameters. The sparsity of the mapping between channel geometrical parameters and coupling elements is also maintained.

Let the vector $\boldsymbol{d}$ of dimension $n$ represent the channel geometrical parameters. 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 channel coarse model (Fig. 1) match those obtained by the EM simulator. There exists a mapping between $\boldsymbol{m}$ and $\boldsymbol{d}$

$$\boldsymbol{m} = \boldsymbol{p}(\boldsymbol{d}) \tag{1}$$

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

$$\boldsymbol{p}(\boldsymbol{d}) - \boldsymbol{m}^* = 0 \tag{2}$$

As in [1] and [2] this nonlinear system of equations is solved iteratively using linear approximation of the mapping in (1).

*A. Optimization Step Computation*

The optimization step computation is modified from the one in [2] to include upper and lower bounds on the design parameters. The residual $\boldsymbol{r}$ is defined by

$$\boldsymbol{r}(\boldsymbol{d}) = \boldsymbol{p}(\boldsymbol{d}) - \boldsymbol{m}^* \tag{3}$$

At the $i$'th 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

$$\boldsymbol{r}(\boldsymbol{d}_i + \boldsymbol{s}) \approx \boldsymbol{r}_i + \boldsymbol{J}_i\, \boldsymbol{s} \tag{4}$$

where $\boldsymbol{r}_i=\boldsymbol{r}(\boldsymbol{d}_i)$, $\boldsymbol{J}_i$ is an approximation of the Jacobian of the mapping $\boldsymbol{p}$. The optimization step $\boldsymbol{s}$ is obtained by minimizing the $l2$- norm of the residual (4) subject to bounds on the design parameters and a trust region on the step $\boldsymbol{s}$

$$\begin{gathered} \boldsymbol{s} = \arg\min_{\boldsymbol{s}} \frac{1}{2}\left\|\boldsymbol{r}_i + \boldsymbol{J}_i\, \boldsymbol{s}\right\|_2^2 \\ \text{subject to} \\ \left\|\boldsymbol{s}\right\|_\infty \le \Delta_i \\ \boldsymbol{l} \le \boldsymbol{d}_i + \boldsymbol{s} \le \boldsymbol{u} \end{gathered} \tag{5}$$

where $\boldsymbol{l}$ and $\boldsymbol{u}$ are vectors of lower and upper bounds, respectively and $\Delta_i$ is the size of the trust region at the $i$'th iteration. The problem in (5) is a quadratic optimization problem with simple bound constraints. It can be solved efficiently by the gradient-projection method in [9]. As in [2] 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 [2]. Broyden formula [1] is also used to update the Jacobian $\boldsymbol{J}$. The initial value of the Jacobian $\boldsymbol{J}$ is approximated by finite difference around the initial design parameters.

*B. Sparsity of the Matrix 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 mapping $\boldsymbol{p}$ in (1) 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. 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 resonator.
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.

## IV. MANIFOLD MULTIPLEXER DESIGN

Assume that the multiplexer has $N$ channels (see Fig. 2). The design procedure to evaluate the manifold dimensions and the channel geometrical parameters 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 $i = 1, 2, \ldots, N$ apply the technique in Section III to evaluate the optimal design parameters of the $i$'th channel.
*Comment*: The starting point for the ($i$+1)'th channel can be obtained by extrapolating the mapping information of the $i$'th channel.

*Step* 3. Get a more accurate model of the multiplexer by replacing the circuit 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 multiplexer model takes into account the effect 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 space mapping technique a number of EM simulations is needed in order to get an initial approximation for the Jacobian $\boldsymbol{J}$ in (4). From experience we notice that the same Jacobian approximation 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.

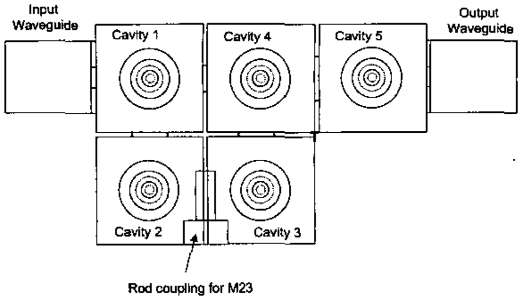

Fig. 3. 5-pole DR filter structure (top view).

## V. MULTIPLEXER DESIGN EXAMPLE

To illustrate the multiplexer design procedure we consider a 10-channel manifold-coupled output multiplexer in the frequency band 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 5-pole DR filter shown in Fig. 3. 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 M2,3 which is realized by a rod coupling [10] (see Fig. 3) for power handling consideration. Ansoft HFSS [8] is used as a fine model of every channel and the network model in Fig. 1 is used as a coarse model. Tuning screws are added to a nominal depth to maximize the tuning range. The T-junctions connecting the channels to the manifold are analyzed by mode matching.

Ideal channels 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. 4 (7 iterations are required). Each channel is then replaced by 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 re-optimized to meet the required specifications. Fig. 5 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. 6. The spurious modes predicted by EM analysis in Fig. 5 correlate very well with the measurements in Fig. 6.

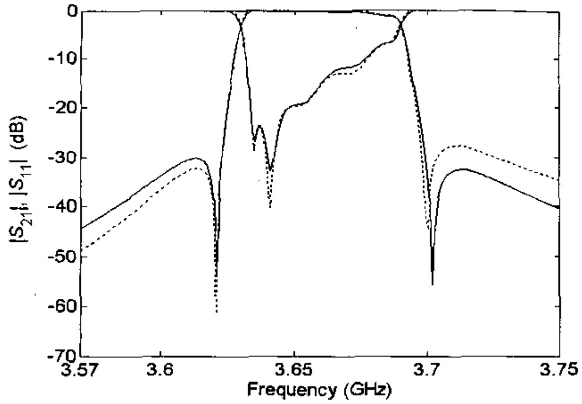


Fig. 4. Responses of the first channel of the 10-channel manifold coupled multiplexer (solid line is the ideal response and dotted line is the EM response at the optimal dimensions).

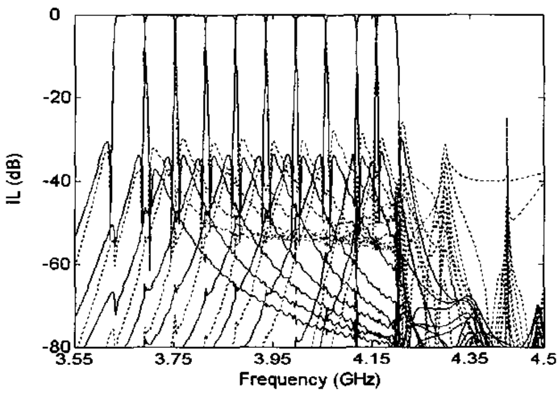


Fig. 5. The ideal response of the 10-channel DR multiplexer (solid line) versus the EM response (dotted line).

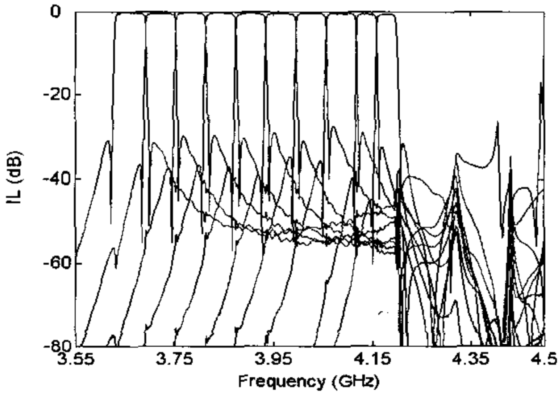


Fig. 6. Measured response of the 10-channel DR multiplexer.

## VI. Conclusion

A new design methodology for DR based channel output multiplexers has been presented. Space-mapping optimization has been used to design the multiplexer channels. Finite Element EM based simulators are used as a fine model of every channel and coupling matrix representation is used as a coarse model. Fine details such as tuning screws are included in the design process. The design procedure results in accurate design of DR multiplexers. A 10-channel output multiplexer is presented to illustrate the multiplexer design procedure.


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