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OPTIMAL DESIGN OF MULTI-CAVITY FILTERS AND CONTIGUOUS-BAND MULTIPLEXERS

J.W. Bandler*+, S.H. Chen*, S. Daijavad* and W. Kellermann*

A general contiguous-band multiplexer optimization procedure exploiting exact network sensitivities is described. The structure under consideration consists of synchronously and asynchronously tuned multi-cavity filters distributed along a waveguide manifold. All design parameters, e.g., waveguide spacings (section lengths), input-output and filter coupling parameters, can be directly optimized using a powerful gradient-based minimax algorithm. Non-ideal effects such as junction susceptances, dissipation and dispersive effects are readily taken into account.

INTRODUCTION

Practical design and manufacture of contiguous-band multiplexers consisting of multi-cavity filters distributed along a waveguide manifold has been a problem of significant interest [1-4]. Recently, a general multiplexer design procedure using an extension of the normal least squares method has been described [5].

Here, we formulate the design of a contiguous-band multiplexer structure as an optimization problem using a recently developed minimax algorithm of Hald and Madsen [6-7]. All design parameters of interest, e.g., waveguide spacings, input-output and filter coupling parameters, can be directly optimized. A wide range of possible multiplexer optimization problems can be formulated and solved by appropriately defining specifications on common port return loss and individual channel insertion loss functions. The minimax error functions are created using those specifications, simulated exact multiplexer responses and weighting factors.

Evaluation of the exact sensitivities for the multiplexer structure is based on the exact sensitivity analysis of individual filters and a direct application of the method of forward and reverse analyses for cascaded structures developed by Bandler, Rizk and Abdel-Malek [8]. Using the narrow-band lumped model of an unterminated multi-cavity filter [2], we present a summary of the required analyses and the sensitivity formulas for such a model. This includes the sensitivity w.r.t. frequency, which is used for the exact group delay evaluation. The unterminated filter can then be terminated by an arbitrary source and load. Therefore, it could be fully embedded into the multiplexer structure for a multiplexer optimization procedure, or by appropriate terminations, it could be considered for a single filter optimal design, if desired.

FORMULATION OF THE PROBLEM

The objective function to be minimized is given by

$$F(\mathbf{x}) = \max_{j \in J} f_j(\mathbf{x}), \tag{1}$$

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where $\mathbf{x}$ is a vector of optimization variables (e.g., section or spacing lengths, channel input and output couplings and filter coupling parameters) and $J \triangleq \{1,2,...,m\}$ is an index set. The minimax functions $f_j(\mathbf{x})$, $j \in J$, can be of the form [9]

$$w_{Uk}^{1}(\omega_i)(F_k^1(\mathbf{x}, \omega_i) - S_{Uk}^{1}(\omega_i)), \tag{2}$$

$$-w_{Lk}^{1}(\omega_i)(F_k^1(\mathbf{x}, \omega_i) - S_{Lk}^{1}(\omega_i)), \tag{3}$$

$$w_{U}^{2}(\omega_i)(F^2(\mathbf{x}, \omega_i) - S_{U}^{2}(\omega_i)), \tag{4}$$

$$-w_{L}^{2}(\omega_i)(F^2(\mathbf{x}, \omega_i) - S_{L}^{2}(\omega_i)), \tag{5}$$

where $F_k^1(\mathbf{x},\omega_i)$ is the insertion loss for the kth channel at the ith frequency, $F^2(\mathbf{x},\omega_i)$ is the return loss at the common port at the ith frequency, $S_{Uk}^1(\omega_i)$ $(S_{Lk}^1(\omega_i))$ is the upper (lower) specification on insertion loss of the kth channel at the ith frequency, $S_U^2(\omega_i)$ $(S_L^2(\omega_i))$ is the upper (lower) specification on return loss at the ith frequency, and w_{Uk}^1, w_{Lk}^1, w_U^2, w_L^2 are the arbitrary user-chosen non-negative weighting factors.

UNTERMINATED FILTER SIMULATION AND SENSITIVITY ANALYSIS

The model of an unterminated multi-cavity filter has been given by Atia and Williams [2] as

$$\mathbf{ZI} = \mathbf{V}, \tag{6}$$

where, for example, the $n \times n$ matrix $\mathbf{Z}$ for a lossless filter may be defined as

$$\mathbf{Z} \triangleq j(s\mathbf{1} + \mathbf{M}), \tag{7}$$

$$s \triangleq \frac{\omega_0}{\Delta\omega}\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right), \tag{8}$$

$\mathbf{1}$ denotes an $n \times n$ identity matrix and $\mathbf{M}$ the $n \times n$ coupling matrix whose (i, j) element represents the normalized coupling between the ith and jth cavities. The diagonal entries M_{ii} represent the deviations from the synchronous tuning. We reduce the system to a two-port given by

$$\begin{bmatrix} I_1 \\ I_n \end{bmatrix} = \mathbf{y}\begin{bmatrix} V_1 \\ V_n \end{bmatrix}, \tag{9}$$

where $\mathbf{y}$ is the s.c. admittance matrix of the filter, including input $1:n_1$ and output $n_2:1$ ideal transformers. Matrix $\mathbf{y}$ and its sensitivities w.r.t. all variables, including frequency, can be obtained by solving the systems

$$\mathbf{Zp} = \mathbf{e}_1 \quad \text{and} \quad \mathbf{Zq} = \mathbf{e}_n, \tag{10}$$

where $\mathbf{e}_1 \triangleq [1\ 0\ \ldots\ 0]^T$ and $\mathbf{e}_n \triangleq [0\ \ldots\ 0\ 1]^T$ are n-dimensional unit excitation vectors. Note that $\mathbf{q}$ can be found with minimal extra effort after factorization of $\mathbf{Z}$ for the solution of $\mathbf{p}$. The following formulas for the evaluation of $\mathbf{y}$ and its sensitivities are readily derived

$$\mathbf{y} = \begin{bmatrix} n_1^2 y_{11} & n_1 n_2 y_{12} \\ n_1 n_2 y_{12} & n_2^2 y_{22} \end{bmatrix} = \begin{bmatrix} n_1^2 p_1 & n_1 n_2 p_n \\ n_1 n_2 p_n & n_2^2 q_n \end{bmatrix}, \tag{11}$$

$$\frac{\partial \mathbf{y}}{\partial M_{\ell k}} = -jc \begin{bmatrix} 2n_1^2 p_\ell p_k & n_1 n_2 (p_\ell q_k + p_k q_\ell) \\ n_1 n_2 (p_\ell q_k + p_k q_\ell) & 2n_2^2 q_\ell q_k \end{bmatrix}, \tag{12}$$

where

$$c = \begin{cases} 1 & \text{if } \ell \neq k, \\ 0.5 & \text{if } \ell = k, \end{cases}$$

$$\frac{\partial \mathbf{y}}{\partial \omega} = -j \frac{\partial s}{\partial \omega} \begin{bmatrix} n_1^2 \mathbf{p}^T \mathbf{p} & n_1 n_2 \mathbf{p}^T \mathbf{q} \\ n_1 n_2 \mathbf{p}^T \mathbf{q} & n_2^2 \mathbf{q}^T \mathbf{q} \end{bmatrix}, \tag{13}$$

$$\frac{\partial \mathbf{y}}{\partial n_1} = \begin{bmatrix} 2n_1 p_1 & n_2 p_n \\ n_2 p_n & 0 \end{bmatrix} \quad \text{and} \quad \frac{\partial \mathbf{y}}{\partial n_2} = \begin{bmatrix} 0 & n_1 p_n \\ n_1 p_n & 2n_2 q_n \end{bmatrix}. \tag{14}$$

COMPUTER IMPLEMENTATION

A Fortran package has been developed for multiplexer simulation, sensitivity analysis and optimization. Functional blocks of the package are shown in Fig. 1. This package has been designed to reflect the requirements of ComDev Ltd. of Cambridge, Ontario, Canada. It has been tested in close cooperation with engineers directly involved in multiplexer design and postproduction tuning. For details see the section on Computational Experience.

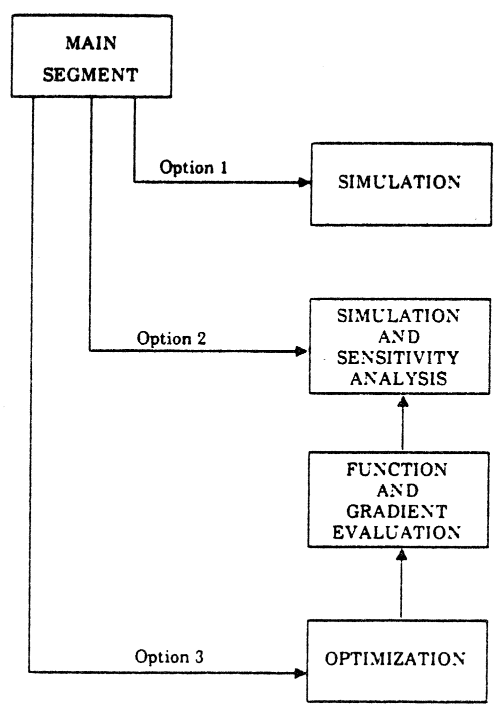

Fig. 1 Functional blocks of the computer package for multiplexer simulation, sensitivity analysis and optimization.

A. Options of the Package

The required mode of operation of the package is selected by the user by setting an indicator as follows:

1 - if only multiplexer simulation is required,
2 - if multiplexer sensitivity analysis is required (implies simulation),
3 - if multiplexer optimization is required (implies both simulation and sensitivity analysis).

B. Options of the Optimization Mode

If the multiplexer optimization option is selected three modes of optimization are allowed for, namely, only return loss optimization (suggested by Chen [4]), only insertion loss optimization, return loss and insertion loss optimization, all at user-defined sets of frequency points. A suitable and sophisticated coding scheme has been developed which creates a consecutively numbered set of minimax functions depending on whether we have only lower (upper) specifications, both or no specifications on a function of interest at a certain frequency point.

C. Options Related to the Selection of Optimization Variables

The coding scheme developed and employed in the package allows also a very flexible choice of optimization variables. In general, all parameters are candidates for optimization variables, however, with very little effort the user can declare any parameters to be optimization variables.

D. Options Related to the Microwave Model of a Multiplexer

The package can exploit three commonly used practical models of the multiplexer, depending on whether the junctions are ideal or nonideal (junction susceptance is included), whether the filters are lossless or lossy (dissipation is included) and whether the filters are modeled as dispersive or non-dispersive. (The waveguide manifold is always assumed dispersive.)

COMPUTATIONAL EXPERIENCE

Test 1 A 12-channel, 12 GHz multiplexer without dummy channels has been optimized using spacings, input-output transformer ratios, cavity resonant frequencies as well as intercavity couplings as optimization variables. A lower specification of 20 dB on return loss has been imposed. The problem involves 60 nonlinear design variables. The filters are assumed lossy and dispersive; waveguide junctions are assumed nonideal. The results of optimization are shown in Fig. 2.

Test 2 A 3-channel, 12 GHz multiplexer without dummy channels has been optimized under the same assumptions as in Test 1 using 45 nonlinear design variables. A lower specification of 20 dB on return loss has been imposed. The results are shown in Fig. 3.

Test 3 An 8-channel, 12 GHz multiplexer has been optimized using spacings as the only variables and specifications on channel insertion loss functions for the 6 middle channels. A lower specification of 20 dB on return loss at the 5 crossover frequencies has also been imposed. The problem involves 8 variables and 65 minimax functions.

The CPU time on the Cyber 170/815 system for the above tests varies from one minute to ten minutes, depending on the number of minimax functions and optimization variables.

CONCLUSIONS

A powerful and efficient optimization procedure for contiguous-band multiplexers has been presented. It employs a fast and robust gradient-based minimax algorithm. The

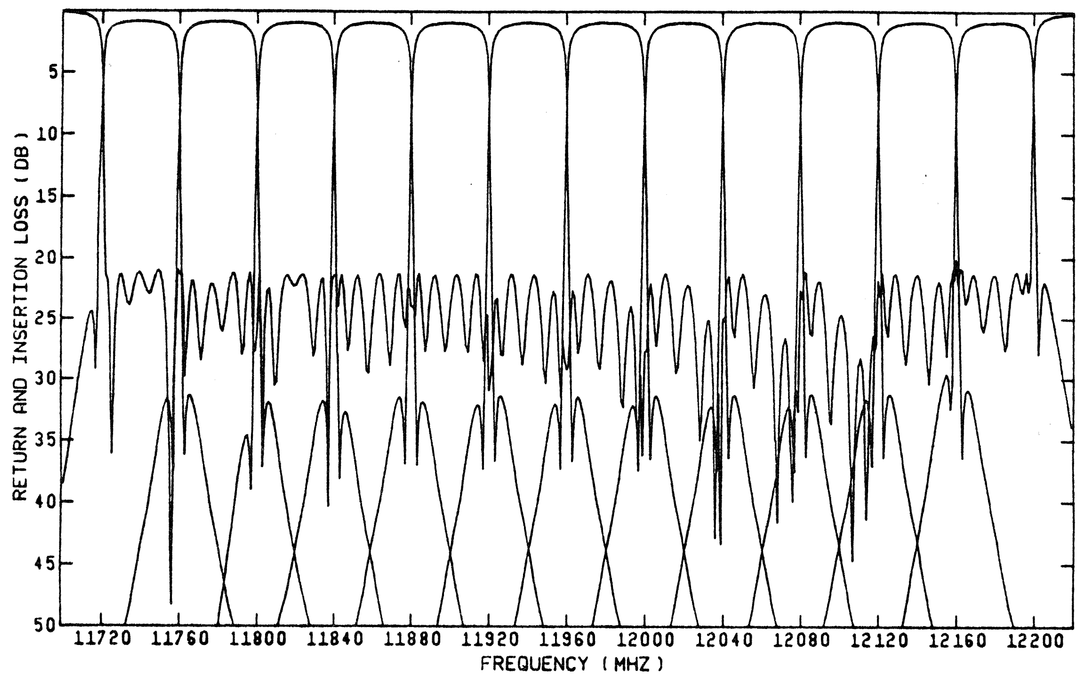

Fig. 2 Responses of a 12-channel multiplexer without dummy channels with optimized spacings, input-output transformer ratios, cavity resonances and coupling parameters.

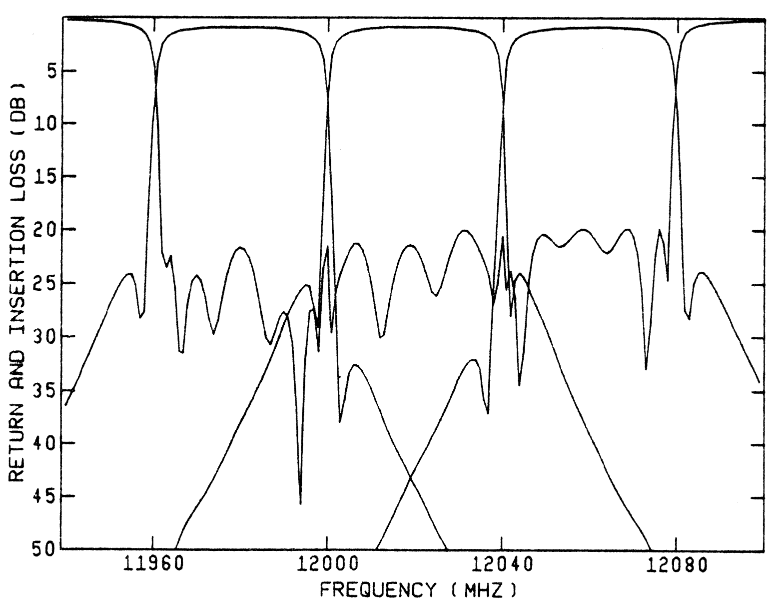

Fig. 3 Responses of a 3-channel multiplexer without dummy channels with optimized spacings, input-output transformer ratios, cavity resonances and coupling parameters.

multiplexer responses and their first-order sensitivities are calculated efficiently and exactly. The Fortran package developed allows flexibility in formulating multiplexer optimization problems of interest as well as flexibility in selecting optimization variables and multiplexer models. It is designed to handle multiplexer structures up to 16 channels with filters of order 8. The package facilitates tests on various candidate models for junctions. An important feature is the possibility of including linear equality and inequality constraints on optimization variables.

Our approach to simulation and sensitivity analysis of the multiplexer structure is easily specialized to single filter design. Optimal design, efficient prediction of nonideal effects such as dissipation and parameter estimation from measured data have been successfully performed on single filters. Currently, work is under way to use accurate interpolation techniques for selection of critical frequency points in both multiplexer and filter design. This will result in significant reduction in the dimensions of the problems to be solved.

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