SIMULATION OPTIMIZATION SYSTEMS
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# CASE STUDY IN PASSIVE CIRCUIT CAD

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# CASE STUDY IN PASSIVE CIRCUIT CAD

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

This tutorial paper reviews some fundamental principles in applying modern optimization techniques to passive microwave circuit design. Nonlinear minimax optimization is stressed, the exploitation of exact partial derivatives of circuit models is used and justified and a suitable case study is presented. The case study is the design of coupled-cavity, narrow-band filters, the results for which are obtained by a powerful interactive optimization package.

## INTRODUCTION

The nominal design of passive microwave devices such as filters is traditionally achieved in two major stages: approximation and realization. For the approximation, a device type suitable for the given specifications is chosen and the device functions are calculated following one of the synthesis procedures, which vary with different device types. Then, for realization, the actual component values of the circuit are calculated.

The tremendous development in communication systems in recent years requires the use of microwave devices such as multiplexers, for which synthesis procedures are tedious or impossible. Moreover, there is a demand for greater variety and more stringent requirements on standard devices such as filters. For instance, asymmetric, non-minimum phase or other special characteristics may be required. As the complexity and requirements of the problems encountered increase, the traditional design approach becomes less feasible or desirable.

Employing modern computer-aided design techniques and directly taking the engineering specifications as optimization objectives and the network parameters as the optimization variables is the commonly accepted approach in design of microwave devices at this time. In this paper, we present a brief review of some principles in the general formulation of design optimization problems [1]. Then, we consider the optimal design of a popular passive microwave device, namely, the multi-cavity filter, to illustrate the convenience in treatment of various engineering specifications using CAD techniques.

## FORMULATION OF THE PROBLEM

A thorough treatment of the general formulation of the design optimization problem has been provided by Bandler [1]. Here, a brief review of some principles is appropriate.

We define the error function as

$$e(\boldsymbol{\phi},\omega) = w(\omega)\,[F(\boldsymbol{\phi},\omega) - S(\omega)], \tag{1}$$

where $\omega$ denotes the frequency variable, the vector

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$$\phi = [\phi_1 \ \phi_2 \dots \phi_n]^T \tag{2}$$

contains the design variables of the network under consideration. $F(\phi,\omega)$ is the network response of interest and $S(\omega)$ the prescribed specification. The weighting function $w(\omega)$ is defined as

$w(\omega) > 0$ corresponds to an upper specification,

$w(\omega) < 0$ corresponds to a lower specification.

It follows that the specification is satisfied when $e(\phi,\omega) \leq 0$, or violated when $e(\phi,\omega) > 0$. Therefore, the objective of optimization becomes essentially

$$\underset{\phi}{\text{Minimize}} \ e(\phi,\omega). \tag{3}$$

In practice, the frequency band of interest is divided into a number of subintervals. Within each subinterval, the specification and the weighting function are kept constant and the error function (1) is discretized in frequency, that is, we evaluate the error function at a finite number of sample points, resulting in a set of discrete error functions, as

$$e_{ij}(\phi) = w_j [F(\phi, \omega_{ij}) - S_j], \qquad i = 1,2,\dots,m_j, \qquad j = 1,2,\dots,k \tag{4}$$

where $m_j$ is the number of sample points of the jth interval and k is the total number of subintervals.

Evaluation of gradients or sensitivity analysis is required by state-of-the-art optimization packages and plays a fundamental role in modern CAD. Of the various techniques available for powerful and robust optimization the minimax approach [1-4] is the most preferred in the optimal design of passive microwave circuits.

## THE CASE STUDY

### A. The Model of Multi-Cavity Filters

An unterminated narrow-band multi-cavity filter [5] can be described by its coupling matrix **M**. Traditionally the filter is designed by choosing the transducer function of a singly- or doubly-terminated model, and constructing the coupling matrix accordingly.

Recently we have developed efficient approaches to the simulation and exact sensitivity evaluation of multi-cavity filters [6,7] treating all the couplings directly as possible variables, including the diagonal elements of **M**, which may represent deviations from synchronous tuning, and the input and output couplings which allow the filter to be embedded into a microwave system.

These approaches have been successfully implemented to develop a computer software system for the simulation, optimal design, efficient prediction of dispersive, junction and dissipation effects and parameter estimation from measured data of the filter network, accommodating various types of specifications and arbitrary terminations.

### B. Filter Design by Optimization

The powerful minimax algorithm of Hald and Madsen [3,4] has been employed to achieve all the optimal designs we present. Usually the error functions are calculated at a large number of fixed points spaced along the frequency axis, thus the optimization package faces a large number of minimax error functions and the solution is not guaranteed to be optimal in the continuous sense since some error peaks may still be missed. To overcome this problem, we have introduced the gradient-based cubic interpolation technique to automatically detect and locate the extrema of the continuous error function using exact derivatives of response w.r.t. frequency. The frequency band of interest is divided into subintervals according to different required specifications. The extremum points located in each subinterval, the edge points and, to stabilize the algorithm, a few fixed points are used in constructing the minimax functions. In this way the dimension of the problem is significantly reduced, and a continuous minimax solution results.

## C. Computational Results

The examples considered are based on a 6-pole model, centered at 4000 MHz with 1% bandwidth. For the multi-coupled cavity filters considered here, a synchronously tuned design, as has been demonstrated by Cameron [8], always realizes electrically symmetric responses, regardless of physical realization. We have solved many such problems. We have also solved problems in which the filters are connected to sources with complex impedances. We have designed filters with optimal group delay characteristics.

For the case study in this tutorial paper we present some results for filters with asynchronous tuning and asymmetrical response characteristics. Detailed and explicit formulas for computation of various responses and sensitivities of interest are available [7]. Here we used the reflection coefficient response as a basis for implementing the error functions for the assumed lossless filters. Space does not permit us to present full details of the parameters necessary to formulate and run the problems, but we provide sufficient information so that our results may be independently verified.

Figures 1-3 show amplitude results corresponding to amplitude specifications. Figure 4 shows amplitude and group delay responses corresponding to simultaneously optimized amplitude and group delay specifications for a synchronously tuned structure.

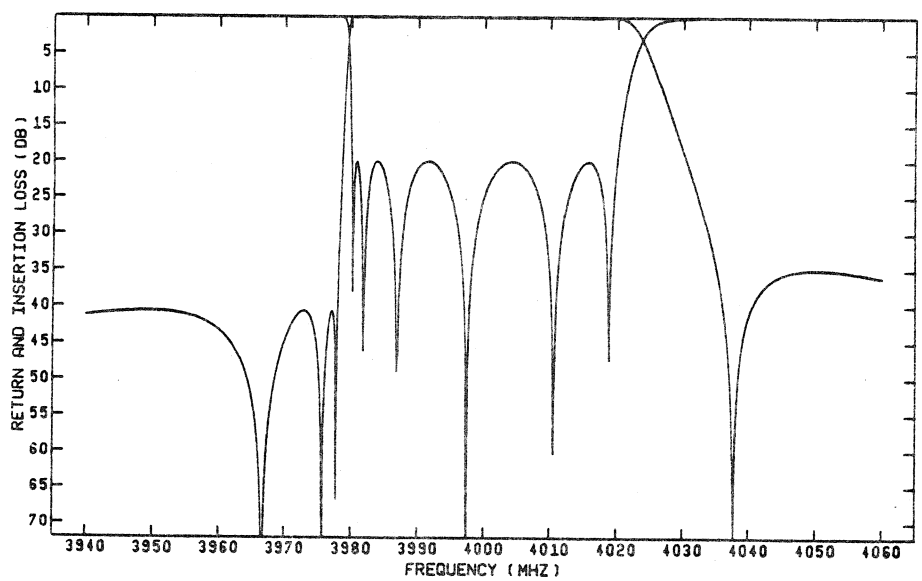



Fig. 1 Return loss (RL) and insertion loss (IL) responses using the reflection coefficient.

Specifications: 3950-3978 MHz, 40 dB IL, $w = -1$
3980-4020 MHz, 20 dB RL, $w = 1$
4035-4050 MHz, 34 dB IL, $w = -1$

Variables: $M_{11}=M_{66}=-0.03315$, $M_{22}=M_{55}=-0.05918$, $M_{33}=M_{44}=0.69943$,
$M_{12}=M_{56}=0.83234$, $M_{23}=M_{45}=0.46166$, $M_{34}=0.29296$,
$M_{16}=-0.07894$, $M_{25}=0.33007$, $M_{15}=M_{26}=0.03999$,
$M_{24}=M_{35}=-0.31780$, $n_1^2 = n_2^2=0.99623$

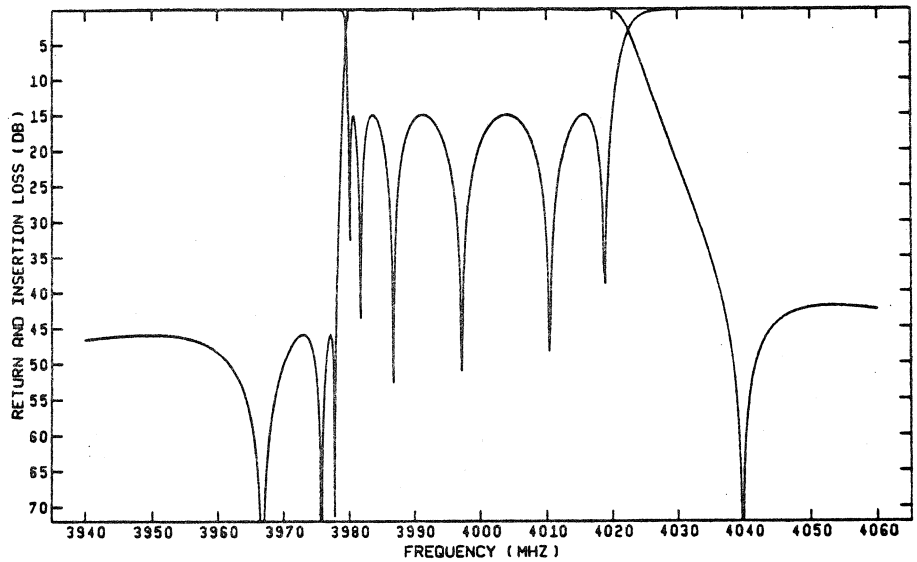



Fig. 2 Return loss (RL) and insertion loss (IL) responses using the reflection coefficient.
Specifications: 3950-3978 MHz, 40 dB IL, w = −1
3980-4020 MHz, 15 dB RL, w = 1
4035-4050 MHz, 34 dB IL, w = −1
Variables: $M_{11}=M_{66}=-0.02439$, $M_{22}=M_{55}=-0.04392$, $M_{33}=M_{44}=0.68523$, $M_{12}=M_{56}=0.75282$, $M_{23}=M_{45}=0.44064$, $M_{34}=0.29111$, $M_{16}=-0.05190$, $M_{25}=0.29976$, $M_{15}=M_{26}=0.02515$, $M_{24}=M_{35}=-0.29633$, $n_1^2= n_2^2=0.79421$

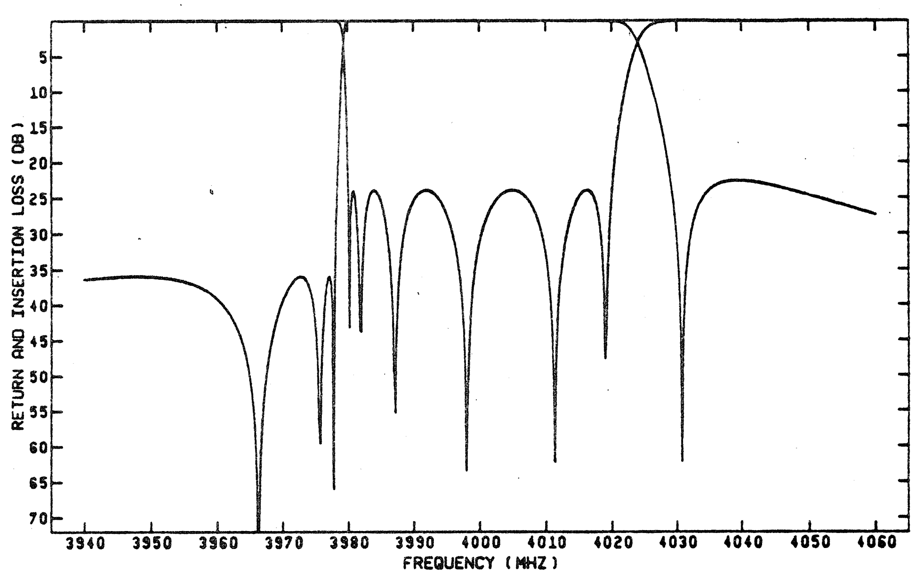
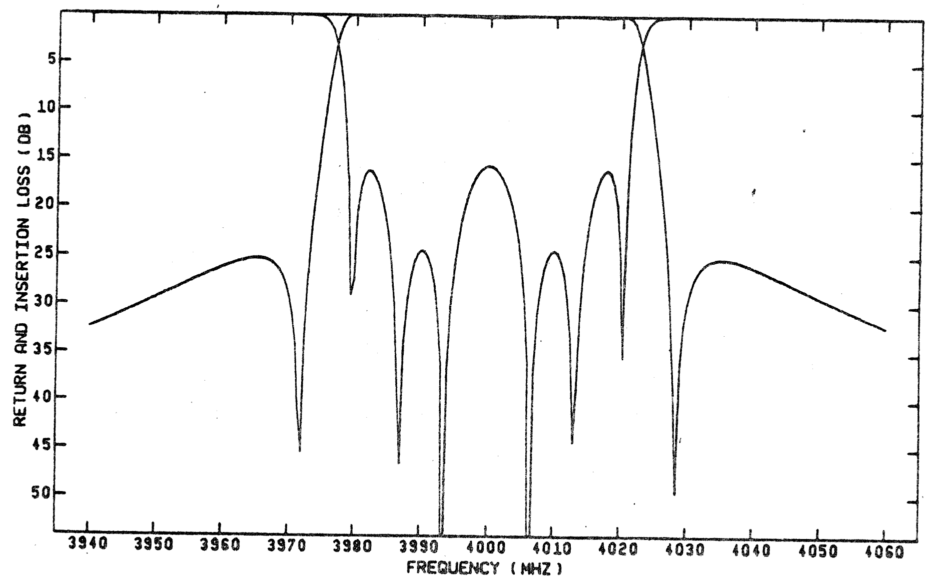
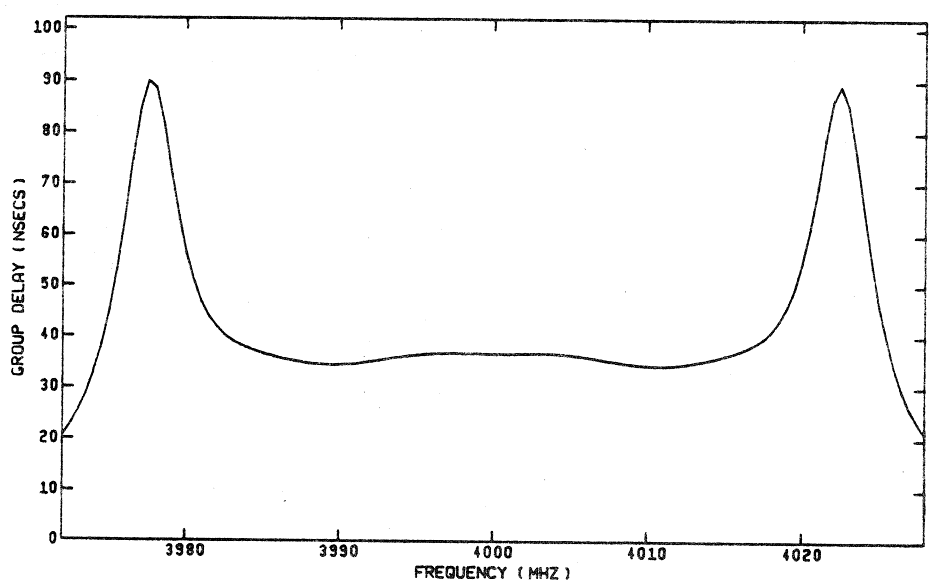



Fig. 3 Return loss (RL) and insertion loss (IL) responses using the reflection coefficient.
Specifications: 3950-3978 MHz, 40 dB IL, w = −100
3980-4020 MHz, 25 dB RL, w = 1
4035-4050 MHz, 34 dB IL, w = −1
Variables: $M_{11}=M_{66}=-0.03313$, $M_{22}=M_{55}=-0.06104$, $M_{33}=M_{44}=0.65638$, $M_{12}=M_{56}=0.88714$, $M_{23}=M_{45}=0.51221$, $M_{34}=0.35007$, $M_{16}=-0.13564$, $M_{25}=0.30060$, $M_{15}=M_{26}=0.09952$, $M_{24}=M_{35}=-0.36416$, $n_1^2=n_2^2=1.14870$




(a) Return loss and insertion loss response.




(b) Group delay response.

Fig. 4 Responses of the synchronously tuned filter showing optimized amplitude and group delay.
Variables: $M_{12}=M_{56}=0.84322$, $M_{23}=M_{45}=0.60733$ $M_{34}=0.62970$, $M_{16}=-0.11003$, $M_{25}=0.03351$, $n_1{}^2=n_2{}^2=0.99826$.

## CONCLUSIONS

A case study for optimal CAD of passive microwave structures has been presented and illustrated. A powerful gradient-based, interactive, user-oriented program has been programmed in Fortran. It offers efficient minimax optimization and accomodates optimal tradeoffs between amplitude and group delay responses for coupled-cavity narrow-band filters. Typical run times on a CDC 170/815 computer vary from 20 to 200 CPU seconds, depending on the starting point, complexity and number of variables involved.

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