Automated CAD of Coupled Resonator Filters

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***Abstract*—A gradient-based optimization technique along with a new definition of cost function is applied to the CAD of coupled resonator filters. The topology of the structure is enforced at each step of optimization and its physical dimensions are used as optimization variables. The cost function is defined using location of zeros and poles of the filter's transfer and reflection functions. Numerical tests show that with the new definition of the cost function, the optimization process converges from an arbitrarily selected starting point. This allows one to design filters even without a rough microwave synthesis which usually provides initial dimensions.**

***Index Terms*—CAD, filters, optimization.**

I. Introduction

In RECENT years, several optimization-based techniques and electromagnetic modeling of an entire structure have been proposed for CAD of coupled resonator filters with a given topology. Successful application of optimization as a CAD tool depends on a suitable definition of cost function. One good choice of the cost function is that of Atia *et al.* [7] or Amari [5]. The cost function is formed by calculating the S_{11} and S_{21} of a structure at the edges of the passband and frequencies which coincide with the location of transmission zeros and poles of synthesized filtering functions. Alternatively [1], the coupling matrix can be identified during the EM analysis and its deviation form the prototype used to formulate the cost function. Both approaches yield excellent results [1], [8] provided that the optimization is preceded by at least a rough filter synthesis which serves as an initial guess. In fact, the synthesis in terms of inverters and electromagnetic characterization of key building blocks is regarded as an indispensable step of successful microwave filter design. This paper presents a new approach to CAD of coupled resonator filters which allows one to find physical parameters of the filter with a given topology without any prior calculations of filter dimensions. A designer is required to specify the topology and a rational function which fulfills the filtering requirements. A gradient-based optimization minimizes then the cost function involving only the roots of polynomials which define the filter's transfer and reflection functions. Physical dimensions of the structure are varied until zeros and poles of reflection and transmission functions reach the desired locations. Obviously, by this means, one cannot design a filter with a given electrical specification if the physical structure does not permit it. In such a case, the optimization method will not converge to the desired solution. Numerical test showed that with the new definition of the cost function, a starting point for a gradient optimization method can be chosen almost at random.

The efficiency of the new method is illustrated on three examples involving an all-pole filter and two band pass filters with a finite number of transmission zeros and symmetric and asymmetric response. All filters were analyzed using the mode-matching (MM) technique and optimized using the sequential quadratic programming (SQP) method available in Matlab Optimization Toolbox [9]. In all cases, only the transmission and reflection functions were synthesized.

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II. Cost Function

Except for a constant scaling factor, each rational function is uniquely determined by the location of its poles and zeros. Calculating poles (P_i) as roots of the denominator and zeros (Z_i) as roots of the numerator of an ideal transfer function, the cost function is defined as follows

$$C=\sum_{i=1}^{M}|Z_i'-Z_i|^2+\sum_{i=1}^{N}|P_i'-P_i|^2 \tag{1}$$

where N is a number of poles, M is a number of (prescribed) transmission zeros, and Z_i's and P_i's are the zeros and poles of a rational function approximation of $S_{21}(\omega)$ for a filter being optimized. The positions of Z_i's and P_i's are calculated for every structure created in the optimization cycle procedure by applying the Cauchy method [4]. The Cauchy method is an interpolation technique which assumes that the approximated function is expressed as a ratio of two polynomials. The coefficients of these polynomials are found by applying the total least squares technique to solve the matrix equations involving the values of the function being approximated evaluated at a few points. Since the topology of the optimized filter is given, the ranks of the polynomials are known. Once the polynomial coefficients in the numerator and denominator have been found, the rooting of the polynomials yields Z_i's and P_i's. After the optimum is reached, the cost function is modified to

$$C=\sum_{i=1}^{N}|P_i'-P_i|^2+\sum_{i=1}^{N}|R_i'-R_i|^2 \tag{2}$$

where R_is are the zeros of the synthesized reflection polynomial function $(S_{11}(\omega))$ and R_i's are the zeros of the numerator polynomial found by the Cauchy method form $S_{11}(\omega)$ computed for a current structure using full-wave analysis.

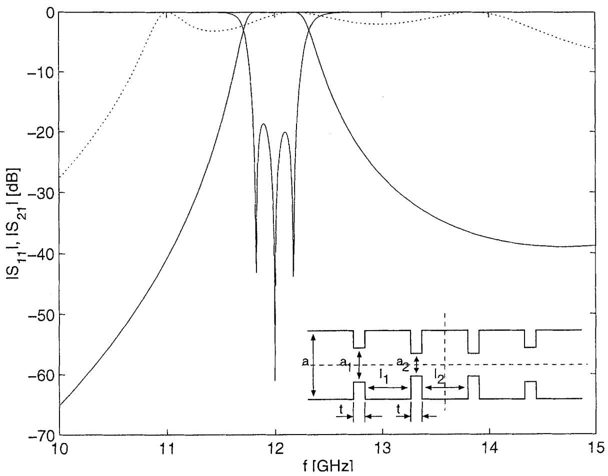

Fig. 1. Scattering parameters of a three-resonator band-pass filter based on the inductive irises after optimization (—) and before optimization (· · ·).

TABLE I
RESULTS OF OPTIMIZATION. THREE-RESONATOR H-PLANE FILTER

Filter	x_{str1}	x_{str2}	x_{str3}	x_{opt}
a_1	13.05	10.0	15.0	9.845
a_2	13.05	10.0	15.0	6.795
l_1	10.00	10.0	15.0	13.218
l_2	10.00	10.0	15.0	14.632

waveguide dimensions: t=2, a=19.05, b=9.525
x_{str1}, x_{str2}, x_{str3} – starting points
x_{opt} – optimized values
All dimensions are in millimeters

III. RESULTS

Using the technique described above, we have designed several filters with different filtering characteristics. In our tests, we used a gradient-based optimization method available in the Matlab Optimization Toolbox [9] to investigate all-pole filters as well as filters with symmetrically and asymmetrically located transmission zeros. No synthesis other than the synthesis of the transmission and reflection functions was performed. The starting point for the optimization was chosen at random within certain limits which were regarded as constraints for the optimizer.

In this paper, we present the results for three filters in which the mode-matching technique was used as a tool for electromagnetic analysis. The optimization was performed using 40 modes and then the filter responses were re-computed using 100 modes.

The initial and final characteristics of the filters with symmetric and asymmetric responses are shown in Figs. 2 and 3. It is seen that, for starting values, the structures do not behave as bandpass filters. As a result of optimization, bandpass characteristics with transmission zeros at desired locations are obtained. As a first example, an all-pole three-resonator bandpass filter based on thick inductive irises in a rectangular waveguide was designed (Fig. 1). Three sets of initial guess and the solutions reached from all three sets by the optimization method are listed in Table I. Fig. 1 shows the initial characteristic calculated for x_{str1} and the characteristics after the optimization. The number of function evaluations was about 700. This number includes function evaluation needed to numerically compute gradients. The number of function calls can, however, be reduced when stricter bounds are imposed on optimized variables. At each time the structure was analyzed at nine frequency points spread uniformly in the desired passband. The transmission and reflection coefficients calculated at these points were used as the

TABLE II
RESULTS OF OPTIMIZATION. DUAL-MODE FILTERS WITH ASYMMETRIC AND SYMMETRIC RESPONSES

	Asymmetric		Symmetric	
x	x_{str}	x_{opt}	x_{str}	x_{opt}
a_1	10.10	10.153	9.027	9.784
a_2	40.00	46.338	27.270	29.932
a_3	10.20	10.593	10.602	10.146
a_4	19.01	25.174	31.052	30.340
a_5	10.10	11.003	10.871	10.178
l_1	2.30	3.277	4.299	2.619
l_2	19.03	26.142	28.645	28.631
l_3	6.10	11.948	12.370	11.859
l_4	19.0	27.994	29.277	28.356
l_5	2.10	4.706	2.413	3.231
s_1	18.0	19.540	1.093	3.157
s_3	4.40	7.291	5.107	2.774

waveguide dimensions: a=19.05, b=9.525
$s_2 = s_1$, $s_4 = s_3$
x_{str} – starting values
x_{opt} – final values
All dimensions are in millimeters

TABLE III
POLES AND TRANSMISSION ZEROS LOCATION OF A DUAL-MODE FILTER WITH SYMMETRIC RESPONSE AFTER TRANSFORMATION TO LOW-PASS PROTOTYPE

	Initial values	Final values
Transmission	$-0.6666 - j6.4667$	$-0.2491 - j1.1797$
Reflection	$-0.2759 + j18.643$	$-0.2475 + j1.1826$
Poles	$-0.9231 - j3.8848$	$-0.7947 - j0.5792$
	$-0.1416 + j4.0696$	$-0.8019 + j0.5802$
Transmission	$+3.0837 + j26.560$	$+j2.0028$
Zeros	$+0.0209 - j9.0969$	$-j2.0778$

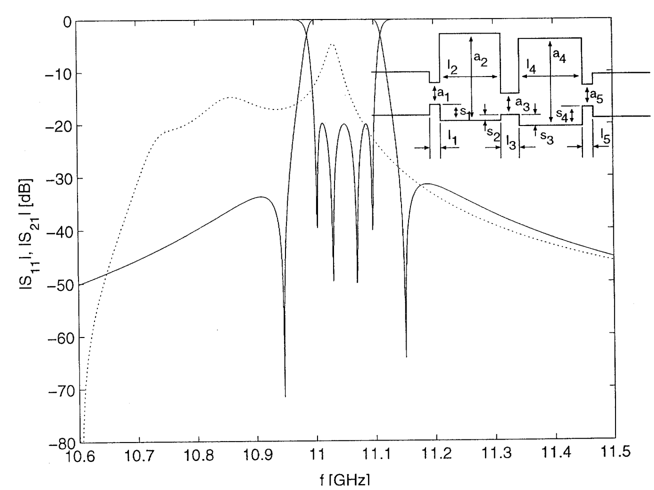

Fig. 2. Scattering parameters of the all-inductive dual-mode filter based on rectangular waveguide after optimization (—) and before optimization (· · ·).

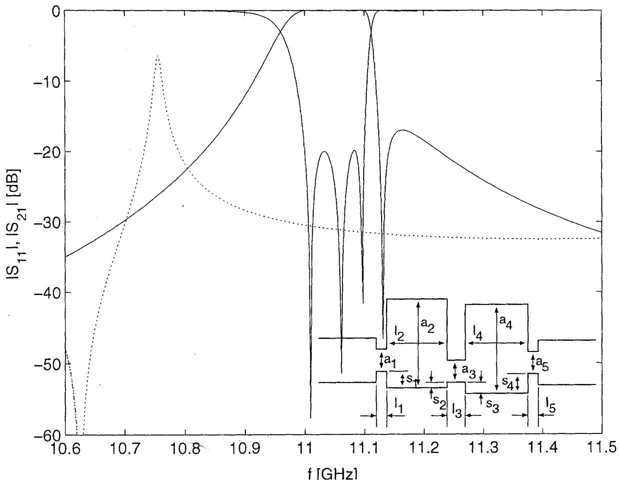

Fig. 3. Scattering parameters of the all-inductive dual-mode filter based on rectangular waveguide after optimization (—) and before optimization (· · ·).

data for the Cauchy interpolation procedure. Total optimization time on a notebook equipped with the Intel 800-MHz processor was 15 min in the Matlab environment.

Next, two all-inductive dual-mode filters based on a rectangular waveguide proposed by Gugliemi *et al.* [2] were designed. Both symmetric and asymmetric characteristics were considered. In each case, 12 variables were optimized simultaneously. Their starting values and the dimensions reached in the optimization process are listed in Table II.

Table III gives the initial and final poles and transmission zeros locations after bandpass to low-pass transformation for the filter with symmetric response. The initial poles and the transmission zeros are located far from the expected ones which corresponds to the high value of the cost function (1). Unstable models that can be created by the application of the Cauchy method during the process of optimization should also be taken into account since they can serve an important role in finding a right direction to the optimum.

For this case, the number of cost function evaluations was 1800. At each cycle of optimization procedure the structure was analyzed at 11 frequency points spread uniformly in the passband. The total optimization time on the aforementioned notebook was 33 min in the Matlab environment. It has to be stressed that this time is shorter than the time on a PC 700 MHz reported for a similar filter in [3], where traditional synthesis techniques were used, each cavity was optimized separately, and the whole filter was subsequently optimized for return loss.

Finally, in order to illustrate the accuracy of the Cauchy method the error norms defined by

$$\varepsilon = \left\| S_{21}^{(mmt)}(\omega) - S_{21}^{(Cauchy)}(\omega) \right\| + \left\| S_{11}^{(mmt)}(\omega) - S_{11}^{(Cauchy)}(\omega) \right\| \quad (3)$$

where $S_{ij}^{(mmt)}$ and S_{ij}^{Cauchy} denote scattering parameters obtained by the MM technique and by the application of Cauchy method, respectively, were calculated. For the dual-mode filters with symmetric and asymmetric responses, the error norms computed in the vicinity of the passbands are equal $8.04 \cdot 10^{-4}$ and $5.2 \cdot 10^{-4}$, respectively.

IV. Conclusion

A new approach to the synthesis of the coupled resonator filters has been presented. Using constrained, gradient-based optimization technique together with a new definition of the cost function, it is possible to design filters with a given topology without the need of synthesis of initial dimensions. Three coupled-resonator filters with symmetric and asymmetric characteristics have been designed to show the validity and effectiveness of the approach.

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