Design of Microwave Band-Pass Filters with Cross-Couplings based on Electromagnetic Simulation and Linear Circuit Optimization

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Cuvinte cheie. *Filtre, microstrip, cuplaje încrucişate, optimizare.*

Rezumat. *Articolul prezintă un studiu asupra posibilităţilor de îmbunătăţire a proiectării filtrelor trece-bandă de microunde cu cuplaje încrucişate, utilizând o procedură hibridă de optimizare. În acest fel toate caracteristicile filtrului, incluzând aici şi localizarea în frecvenţă a polilor de atenuare, pot fi precis controlate, permiţând proiectarea unor filtre trece-bandă cu selectivitate îmbunătăţită. Drept exemplu, configuraţia de filtru trece-bandă considerată a fost proiectată folosind simularea electromagnetică iar performanţele sale au fost optimizate utilizând simularea de circuite liniare. Performanţele filtrului concordă bine cu specificaţia, ceea ce validează posibilităţile de proiectare mai precisă a unor filtre trece-bandă de microunde selective, utile în sistemele actuale de comunicaţii.*

Keywords. *Filters, microstrip, cross-couplings, optimization.*

Abstract. *In this paper are investigated the possibilities of improving the design of microwave filters with cross-couplings by using a hybrid optimization procedure. This way the characteristics of the filter, including the position of attenuation poles in the stopband, can be precisely controlled, allowing the design of band-pass filters with improved selectivity. As a design example, a usual configuration was considered and a filter was designed by using this method. The designed filter was electromagnetically simulated. The responses of the filter are in good agreement with the theory, confirming the possibilities of accurately designing planar microwave band-pass filters with moderate losses and with improved adjacent channel selectivity.*

1. Introduction

The[*] attenuation poles in the transfer characteristic of a band-pass filter are conditioned by the presence of one or more cross-couplings between the filter's resonators [1]. The number of attenuation poles cannot be greater than the order of the filter, i.e. the number of resonators in its structure.

The synthesis of filters with different characteristics is based on the use of the generalized normalized coupling matrix **M**. For a filter of order *N* this matrix has *N* + 2 rows and columns and contains, in a normalized form, all the coupling coefficients between resonators, all couplings between resonators and the access lines represented by the corresponding loaded *Q*'s of the resonators, and all frequency offsets of the individual resonators with respect to the central frequency of the filter. Through

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a straightforward de-normalization procedure, all these parameters defining the properties of a filter can be derived from **M** [2].

The normalized matrix **M** corresponding to some given filter specifications can be obtained through a basic synthesis procedure. For certain usual structures, the synthesis of **M** is presented in [2], [3].

The design of microwave band-pass filter starts from a synthesized **M** matrix and ends by generating a planar layout corresponding as well as possible to the values in **M**.

The object of this paper is to investigate the possibilities of designing filters with unusual resonator and coupling configurations and to improve this design by some optimization procedures. The analysis was focused on the fourth-order filters because the quadruplet with cross-couplings was intensively studied in the last years [3].

2. Design of a fourth-order filter, with two prescribed attenuation poles

To illustrate the design procedure a band-pass filter of order four was designed, with the next specification:

- central frequency 3GHz;
- fractional bandwidth 2.5% (bandwidth 75MHz, cutoff frequencies 2.9625GHz and 3.0375GHz);
- 50 Ohms terminal impedances;
- Chebyshev response with a 0.46dB ripple in the passband, corresponding to a return loss of 10dB;
- two symmetrical attenuation poles, located at normalized frequencies ±1.5 (f_1 = 2.944GHz, f_2 = = 3.056GHz).

Starting with these specifications, a fourth-order filter with the structure presented in Fig. 1, containing a cross-coupling 1 – 4, was chosen. The corresponding normalized matrix **M** was found by using a home-made program, based on the methods presented in [3] and [4]:

$$\mathbf{M}=\begin{bmatrix} 0 & -0.77646 & 0 & 0 & 0 & 0 \\ -0.77646 & 0 & -0.67649 & 0 & -0.18150 & 0 \\ 0 & -0.67649 & 0 & -0.69872 & 0 & 0 \\ 0 & 0 & -0.69872 & 0 & 0.67649 & 0 \\ 0 & -0.18150 & 0 & 0.67649 & 0 & 0.77646 \\ 0 & 0 & 0 & 0 & 0.77646 & 0 \end{bmatrix}$$

The non-zero couplings needed for the implementation of this filter can be seen in Fig. 1.

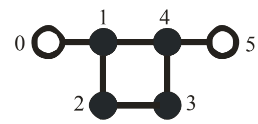

Fig. 1. Couplings in the chosen filter configuration.

This synthesized matrix **M** can be verified by considering a simple model of the filter composed of ideal lumped resonators and ideal admittance inverters, with an arbitrary center frequency and arbitrary terminations. Choosing a central frequency of 3GHz, tuning capacitors of 1.111nF and terminations of 50Ω, the characteristic admittances of the inverters corresponding to these couplings, disregarding their signs, are:

Table 1

$J_{in-1} = J_{4-out}$	$J_{1-2} = J_{3-4}$	J_{2-3}	J_{1-4}
0.07946	0.3542	0.3658	0.09503

This model is presented in Fig. 2 and its response, obtained with circuit simulation software [5], is shown in Fig. 3. It is easy to notice the perfect match of this response with the filter specifications.

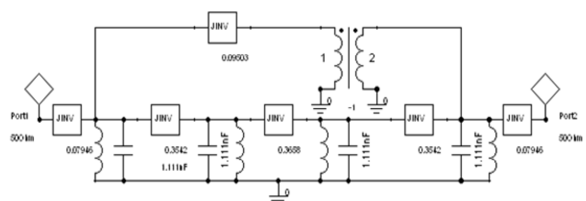

Fig. 2. Normalized model of the band-pass filter, with lumped resonators and ideal admittance inverters.

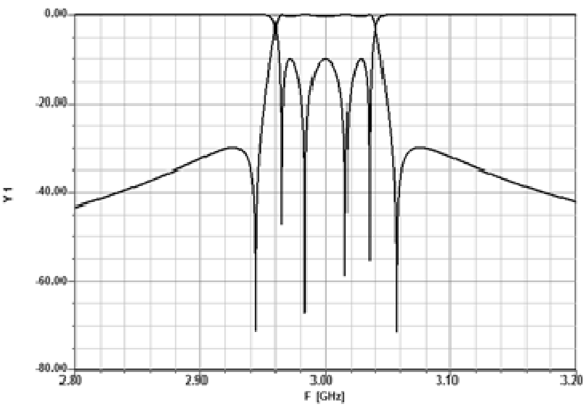

Fig. 3. Simulated response of the normalized filter from Fig. 2.

The microwave filter was designed accordingly to the filter specifications mentioned above, on a Rogers 3003 substrate with a thickness of 20 mils (0.508 mm) and a relative permittivity of 3. This substrate was chosen due to its low losses, tanδ = = 0.0013 at 3 GHz.

The parameters of the microwave band-pass filter were obtained from the matrix **M** through de-normalization:

$$Q_{ext.1} = \frac{1}{wM_{01}^2}; \quad Q_{ext.4} = \frac{1}{wM_{45}^2}. \tag{1}$$

$$k_{ij} = wM_{ij}, \; i, j = 1...4 \; , \quad . \tag{2}$$

For the designed filter, the values from Table 2 were obtained:

Table 2

$Q_{ext.1} = Q_{ext.4}$	$k_{12} = k_{34}$	k_{23}	k_{34}
66.35	0.0169	0.0175	0.0045

The design of the microwave planar band-pass filter was based on electromagnetic field simulations, controlling separately the resonances of the resonators, the couplings between them and the couplings between the end resonators with the access line [3]. The designed layout is shown in Fig. 4.

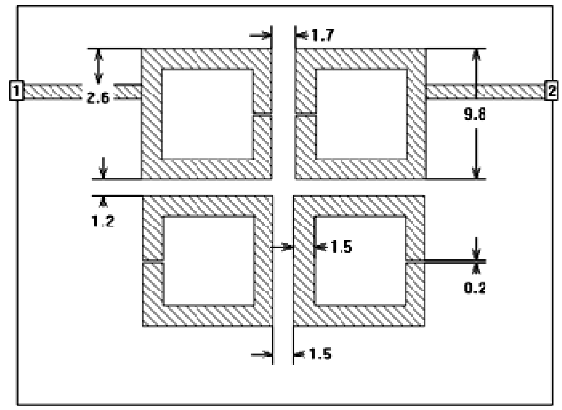

Fig. 4. The microstrip structure of the designed filter with four open-square resonators and with a cross-coupling between resonators 1 and 4.

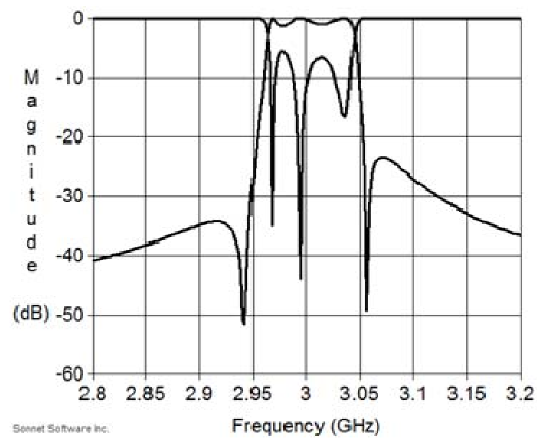

Fig. 5. Simulated response of the lossless microstrip structure shown in Fig. 4.

The designed structure was then tested by using [6]. The results of the simulation are shown in Fig. 5. Generally speaking the simulated results are in good agreement with the filter specifications, but some significant differences can be however noticed.

Part of these differences can be explained by the limited resolution of the grid in the layout design, resolution chosen based on the expected technological tolerances, but some other differences seem to be related rather to an imperfect control of the couplings [5]. At least partially, these differences can be corrected through optimization.

Unfortunately a direct optimization procedure, including a number of variable geometrical parameters in its loop, implies extremely large computing times and resources, being practically out of question. A solution to this problem is to apply a hybrid optimization procedure, combining the accuracy of the electromagnetic field simulation with the rapidity and convenience of the linear circuit analysis and optimization. The basic idea is to add some extra ports to the resonators of the designed layout, ports that allow the interconnection with some external elements [6]. An electromagnetic field simulation can capture all the actual couplings between ports in the layout, no matter if desired or not, if visible or not. The external (variable) reactances can then be connected between an extra port and ground for the correction of the individual resonance frequency, or between two such extra ports, for the correction of the corresponding coupling coefficient. The layout with multiple ports, together with the external elements, is then optimized by using linear circuit simulation software. The values of the external reactances issued from the optimization procedure are representing the errors existing in the layout design. The errors detected in the layout are then corrected, by reconsidering the elements and the pairs of elements in the filter. Using extra ports, the needed corrections can be achieved in a controlled manner.

All the detected errors being corrected, the resulting layout can be considered, in turn, as a new iteration ready to be used as a starting point for a new optimization cycle and so on, certainly not beyond a limit imposed by the expected execution tolerances.

In the design presented in this paper, the most important error was found to be the error in the resonant frequency of the end resonators 1 and 4, error generated by the couplings with the access lines. It seems that this happens in all filter designs.

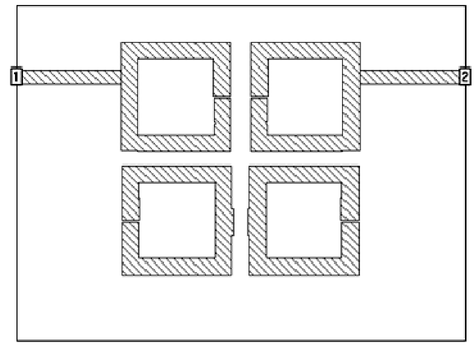

Fig. 6. Layout of the filter, after optimization.

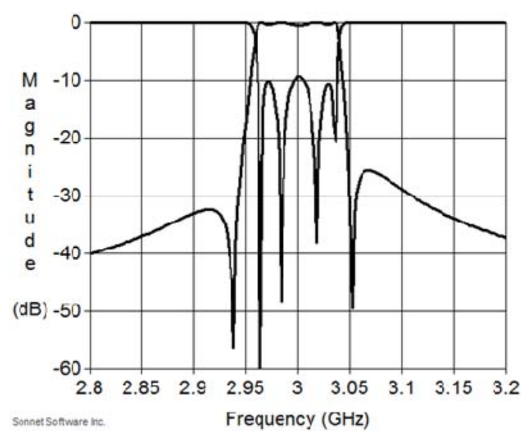

Fig. 7. Simulated characteristics of the optimized filter.

The optimized layout of the designed filter is shown in Fig. 6. It differs from the previous only by many small geometrical details. The regular shapes of the resonators were slightly modified, allowing this way the necessary corrections in the individual resonance frequencies and/or coupling coefficients.

The simulated results of this new layout (Fig. 7) are showing considerably improved characteristics, which now are much closed to the desired curves of Fig. 3, what means that the applied hybrid optimization procedure is very effective.

Finally, including all expected losses in the simulation, the results in Fig. 8 were obtained. It can be noticed that designed filter has a moderate insertion loss, despite its narrow bandwidth, as a consequence of its low order [2].

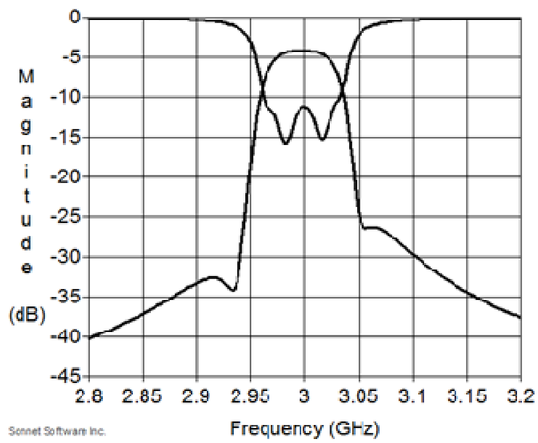

Fig. 8. Simulated response of the filter, considering the losses.

The final form of the characteristic shown in Fig. 8 can be improved even more, through a new hybrid optimization procedure applied this time to the real, lossy structure of the filter.

3. Conclusions

The method of designing microwave band-pass filters by electromagnetic field simulations combined with optimization procedures based on rapid circuit simulation allows a precise design of filters with very convenient properties, even in non-conventional configurations. The design example proofs the power of this hybrid design method, which brings together the accuracy of electromagnetic simulation with the speed and convenience of the linear circuit analysis.

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