Congresso de Métodos Numéricos em Engenharia 2015
Lisboa, 29 de Junho a 2 de Julho, 2015

OPTIMIZATION METHOD FOR THE DESIGN OF MICROWAVE FILTERS BASED ON SEQUENTIAL STAGES

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Keywords: Combline filter, Microwave cavity, Optimization method by stages.

Abstract *Microwave filter design can be done using different approaches. These types of filters are typically found in the front-end of high-frequency transceivers of very diverse systems such as radar, satellite TV or microwave links. This paper addresses the strategy of subdividing the design process into minor stages, each of which takes into account less degrees of freedom (i.e. parameters of design) than in a direct global design. This work evidences how optimization divided into simpler stages becomes an excellent approach to accomplish this task, making it possible to achieve the level of refinement that the physical design parameters require to reach the desired partial responses. The advantages of this approach are discussed with a case of study based on a sixth-order combline cavity bandpass filter for application in base stations of wireless communications.*

1. INTRODUCTION

A microwave filter is a passive device in charge of the signal frequency selection in the context of a communication system [1][2]. Filter design can be addressed by means of electromagnetic solvers implemented in Computer Aided Design (CAD) tools, together with the use of a circuital approach. The use of an equivalent circuit model allows not only to identify (when possible) the different parts of the physical structure under design with their circuital counterpart, but to set the whole desired response that has to be achieved with the cavity filter structure [2].

In this work different stages of approximation are proposed to design microwave cavity filters [2] with the aim of reducing the complexity of the problem. It is important to note that the accurate analysis of a microwave filter involves solving Maxwell´s equations in the structure under analysis and, thus, the evaluation of cost functions in optimization methods may take several minutes. The performance of a microwave cavity filter is determined by its Scattering S-parameters [1][2], which are typically obtained (depending on the solver) by a Finite-Element Method or Finite Difference Method. The response of a microwave filter (i.e., its S-parameters) obtained using a numerical method solving Maxwell´s equations in the physical structure is called *full-wave response*. Although circuit responses are very fast to obtain, full-wave responses (the response closest to what you would measure after an eventual construction of the filter) are very time consuming and demand a lot of RAM in the computer.

Therefore, design and optimization methods for microwave cavity filters should avoid problems with a large number of variables and involving many evaluations of the cost function. On the other hand, a “divide and conquer” strategy, as the approach in this paper, could be more efficient. Each stage uses the results obtained in the previous one, which takes into account a lower number of design elements. The evolution from one stage to another occurs when the full wave response (i.e. that accurate response obtained with an electromagnetic simulator) and the one obtained from the equivalent circuit model are ideally coincident after a refinement optimization process.

The purpose of this work is to emphasize the advantages of an optimization process subdivided into stages with a practical example of a so-called combline filter for base station applications in wireless communications [3][4]. This approach is an excellent alternative to a direct global design, indeed more complex in conceptual and computational terms.

2. STATEMENT OF THE PROBLEM

A combline cavity filter is shown in figure 1 [1]-[4]. The cylindrical cavities correspond to resonators and each resonator has two metallic elements: an internal post and the outer enclosure. The metallic post is shorted at one end with the enclosure, and its length is slightly shorter than a quarter of wavelength at the center frequency of the filter [3]. The cavities are not fully isolated since they have an open region between them that is used to couple them [2]. In the circuit model, these apertures, also called irises or windows are represented by circuit elements called inverters. Moreover, the first/last cavities are also coupled to the coaxial lines used for the input/output of the microwave signal.

In particular, figure 1 is a six order filter that can be used to realize filtering functions of the Chebychev-type [1]-[3]. The goal of this paper is to present a method to design a filter by dividing the whole design into simple stages. The design process must provide the physical dimensions of a structure like that in figure 1, whose full-wave response must fulfill (i.e. *approximate*) the aimed circuital filtering response set as goal. The physical dimensions involved in the design process of this filter are: the inner lengths of the posts (Li_n, n is used to reference each post, since they can be different in each resonator), the height of the coaxial feed lines at the input/output (h_f) and the distance between resonators (dc_n). The radius of the cavities (R_e), the inner posts (R_i) and the feeds (R_{ce}, R_{ci}) are considered as fixed parameters previously set. Figure 2 depicts all these parameters for the physical structure representing a six order filter (having six cavities). The filter is symmetric with respect to plane yz and plane xy; thus, only the dimensions of half of the filter need to be specified. In figure 1 it is only represented the model to be analyzed with the full-wave method; the outer walls of an eventual physical construction are not plotted.

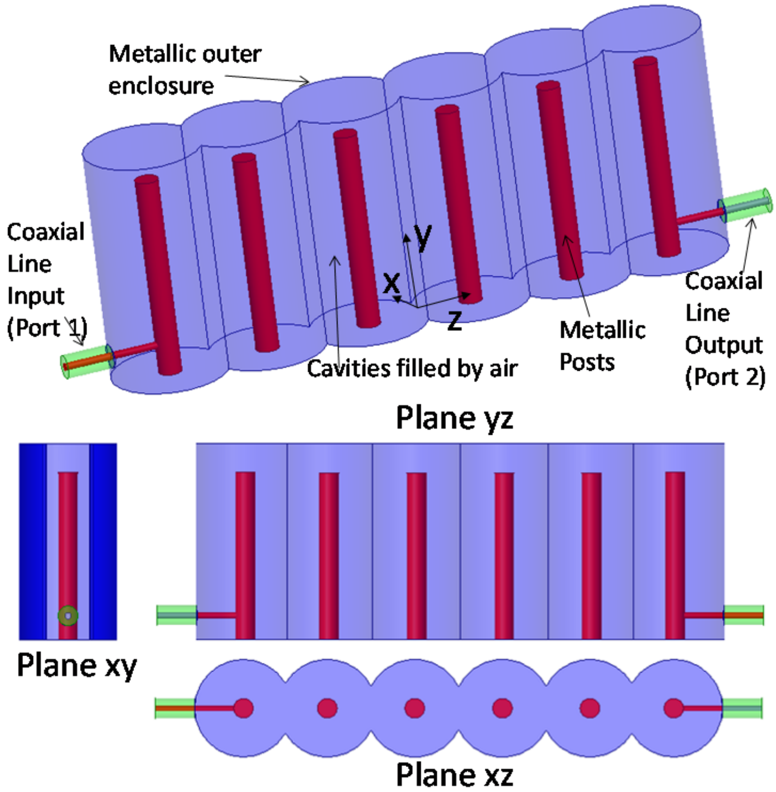


Figure 1. Six-order cavity combline microwave filter. Main views of the physical structure.

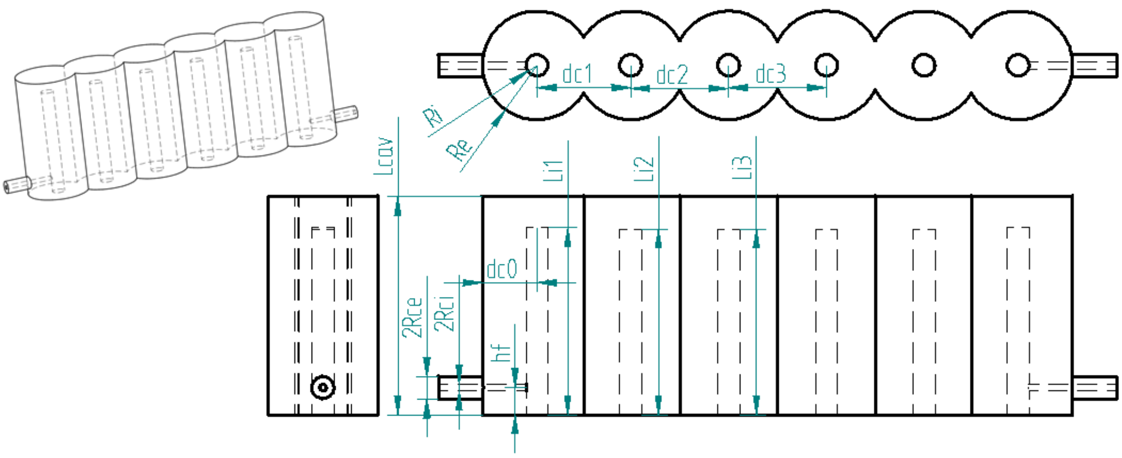


Figure 2. Physical dimensions involved in the design of a combline microwave filter.

The filtering response to be achieved with this physical structure is specified by the so-called coupling matrix **M** [3][5]. The case under consideration is an inline structure [3], where the coupling matrix reduces to only the couplings between adjacent resonators. For a symmetric six-order filter, only three values are needed $M_{1,2}$=$M_{5,6}$, $M_{2,3}$=$M_{4,5}$, $M_{3,4}$, that are mainly controlled by dc_1, dc_2, dc_3, respectively. Input-output couplings M_{in}=M_{out} are controlled by h_f. The resonant frequency of the cavities will be determined by L_{i1},L_{i2},L_{i3}. It is emphasized here that although these parameters control the response of the filter, their values affect not only to one circuit parameter, but to several of them. As a summary, the filter design problem can be stated as: given the coupling values $M_{1,2}$, $M_{2,3}$, $M_{3,4}$, M_{in}, center frequency f_0 and bandwidth *bw* of the desired circuit filtering response, find the dimensions L_{i1}, L_{i2}, L_{i3}, h_f, dc_1, dc_2, dc_3 of a physical combline structure whose full-wave response matches (approximates) the desired circuit response. The next sections will explain how to approach this problem by stages.

3. DESCRIPTION OF THE DESIGN METHOD

3.1. Stages

In each design stage a part of the structure is selected and the electromagnetic simulation is compared with the ideal circuital response correspondent to that part. For convenience the following stages can be represented by means of the pertinent diagram of figure 3, in which circles represent cavities and $M_{i,j}$ describes the coupling (inverters in the circuit model [2]) between resonators. In this way, the four stages selected in this design are represented schematically in figure 3, where M_{in}=M_{out}.

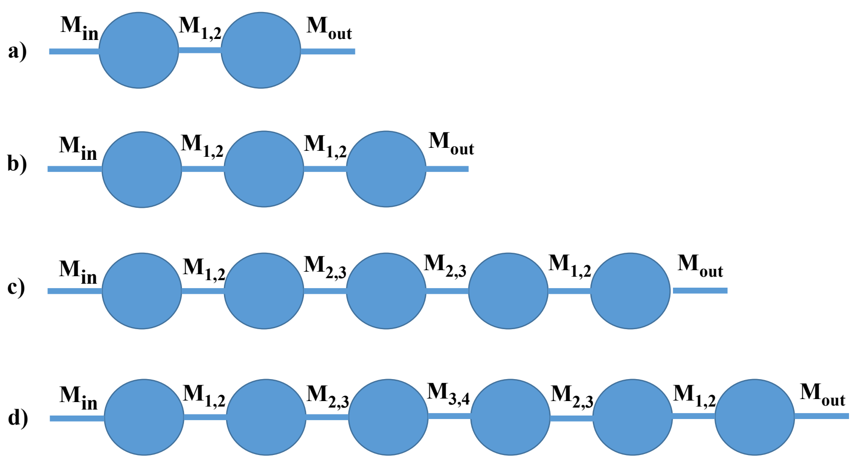


Figure 3. Schematic representation of the stages of the filter design: a) first stage, b) second stage, c) third stage, d) fourth stage (final desired filter).

3.2. Optimization method

Each stage design can be mathematically understood as a problem in which the physical parameters of the structure are variables which lead to an optimal solution – the one implementing the circuit response identified as a target. Three tools are involved in the optimization process: the cost function, the target mask and the optimization algorithm.

The physical dimensions presented in the preceding section are the variables upon which the cost function is dependent. The function to be minimized in this article is the following, comparing the full-wave and circuit responses (given by its S-parameters) at some selected critical frequencies:

$$f(\vec{x}) = \sum_{i=1}^{N} \alpha_i(|S_{21}^{full\,wave}(f_i)| - |S_{21}^{circuital}(f_i)|)^2 + \\ + \sum_{j=1}^{M} \beta_j(|S_{11}^{full\,wave}(f_j)| - |S_{11}^{circuital}(f_j)|)^2, \tag{1}$$

where $\vec{x}$ will be the optimization variables at each stage. The previous cost function is assessed in terms of discrete frequencies conveniently chosen by the designer depending on the optimization stage [6]. These frequencies are also involved in the second tool, which is fundamental for the optimization process – the mask. This article presents several mask types in order to attain the target circuit responses. Finally, the algorithm [7] used to minimize the cost function is the third and last tool of the process. In this particular case, a local-deterministic algorithm able to find minima in no-linear functions is enough.

4. APPLICATION OF THE DESIGN METHOD TO A MICROWAVE FILTER FOR BASE STATIONS

In order to validate the proposed design approach, a sixth-order Chebychev filter, with 20 dB of return loss is proposed. It is centered at f_0=2 GHz with a fractional bandwidth bw=1%, and $M_{1,2}$=0.843, $M_{2,3}$=0.611, $M_{3,4}$=0.583, M_{in}=M_{out}=1.002. This would be a typical scenario for narrow-band filters used in base stations for wireless communications [4]. The combination of the three optimization tools (cost function, mask and algorithm) during the fourth selected stages of design is presented below. In the stages over which the optimization process takes place, simplex algorithm by Nelder Mead is used [7], except in the second stage, in which Trust Region Framework is used.

Dimensions obtained at the end of each stage become the starting point of the next one. In all the stages, an initial task of coarse approximation of the physical parameters incorporated at that stage (and not used in previous stages) is done before the starting the optimization process. Initial values for all the variables can be found using models as those in [8],[9]. During the stages, the cost function (1) will be evaluated with S-parameters in natural units or in logarithmic (dB) units [2]. The representation in the figures will be realized in the domain used for the optimization.

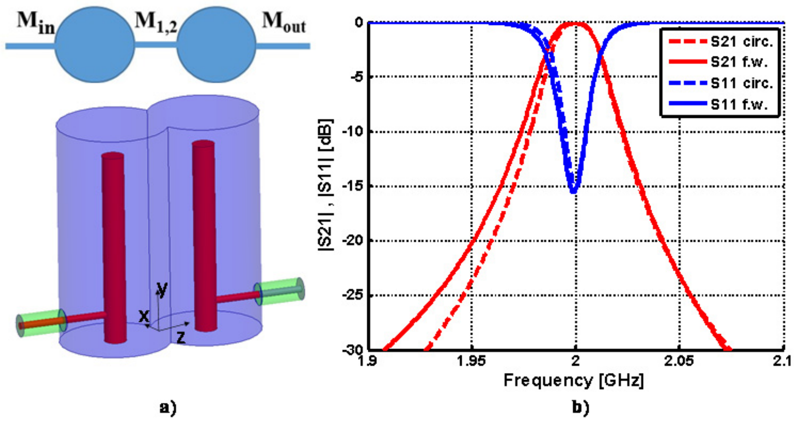


Figure 4. a) Simulated physical structure. b) End of the first stage.

4.1. First stage

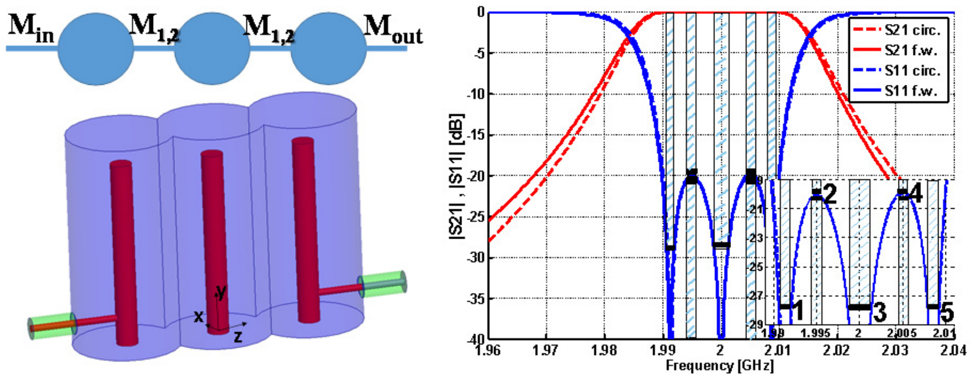
The first step in the design process takes exclusively into account the two resonators placed at both ends of the structure (see figure 3.a and 4.a). Thanks to the small number of variables present at this stage (i.e. only h_f, d_{c1} and L_{i1}, because of the xy-plane symmetry of the structure), even the optimization tool can be replaced by a parametric sweep. The result is shown in figure 4.b, where from now on the label *f.w.* refers to full wave response and the label *circ.* to circuit response.

4.2. Second stage

At this stage the three resonators shown in figures 3.b and 5.a are studied, and therefore the physical design parameters involved are h_f, dc_1, L_{i1} and L_{i2}. This last variable is the only dimension that was not present at previous stage. Thus, the goal of this stage is to set the right value for L_{i2}, while the values of h_f, dc_1, L_{i1} are slightly refined due to the loading effect of the new resonator not considered at the first stage. This is one of the advantages of this strategy: at each stage, new variables are introduced gradually, while previous ones are refined at the same time, and the complexity is increased very smoothly.

For our particular case, the target circuit response at this stage is very similar to the response of a three order filter designed to achieve the same reflection. Since their values do not differ greatly, and the bandwidth obtained in the former is much wider than in the latter, it is decided to use a section mask based on the latter, which is less restrictive. Additional resonators incorporated in the following stages will cooperate to achieve the desired mask. In this particular premature partial stage this is not essential. The result of the optimization process is shown in figure 5.b. together with the details of the mask used by sections only for the reflection. The following weights are used for the cost function by sections $\beta_{section\ 1,3,5} = 0.4,\ \beta_{section\ 2,4} = 0.75$.

For convenience hereinafter the physical structure selected at each stage will be depicted in the same figure where either the starting or ending point of the stage is showed.



a) b)

Figure 5. a) Simulated physical structure. b) End of the second stage.

4.3. Third stage

In the third stage, the five resonators detailed in figure 3.c are used. The physical design parameters involved now are h_f, dc_1, dc_2, L_{i1}, L_{i2} and L_{i3} (again only half of the structure because of the xy-symmetry). Figure 6.a shows the immediately preceding point to the optimization process. Changing from three to five resonators entails a large variation of the loading effect seen by each resonator, which implies a more cumbersome refining process than in the previous stage. Therefore, the optimization work is carried out in several iterations by masks seeking to enhance and correct several aspects of the full-wave response until a trade-off situation is reached. In this context, it is fundamental to define suitable weights α_i and β_i in the cost function. To this end dotted masks instead of section masks are widely used, because the complex nature of this stage requires a more precise control over the selected weights. When dotted masks are used, such dots are depicted by crosses on the target response to which they belong.

Figure 6.b. shows how a dotted circuital optimization mask overlaps with the starting point response in natural units. This mask aims at recovering the transmission bandwidth, and therefore the selected weights are $\alpha_{1\ldots6,\neq3,4} = 1$, $\alpha_{3,4} = 10$, $\beta_{1\ldots11} = 1$.

Figure 6.c. depicts a circuital optimization mask based on levels that has been selected with the purpose of allowing the remaining two reflection zeros to appear. This aims at avoiding that the highly restrictive dotted mask prevents them from appearing. The following weights by sections are used: $\alpha_{section\ 1} = 100$, $\alpha_{section\ 2} = 150$, $\beta_{unique\ section} = 1$.

Figure 6.d. shows the response obtained after the use of the preceding mask, whose primary objective was to locate the remaining two reflection zeros. The algorithm evolution over that iteration did not show the five reflection zeros, but at least a fourth zero was obtained (figure 6.d is detailed in logarithmic units for the purpose of noticeably displaying the achieved reflection zeros).

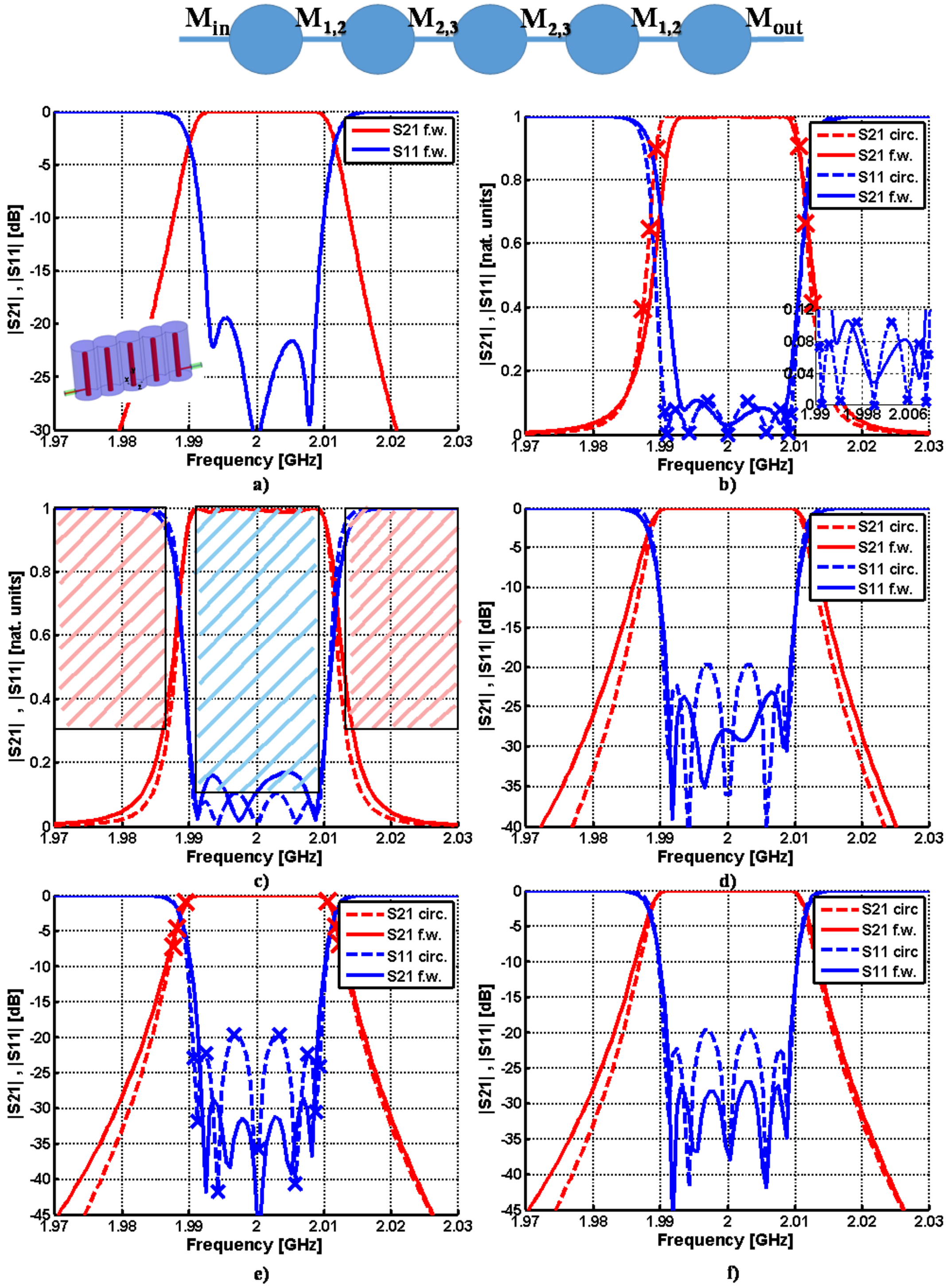


Figure 6. Responses of the most representative iterations of the second stage.

Several intermediate iterations are done with dotted circuital masks whose main goal is to obtain the remaining reflection zeros and to keep the achieved transmission bandwidth. It is important to highlight that sometimes the weights (α_i, β_i) selected lead to the lack of one of the reflection zeros, but this iterative process requires taking such decisions in order to avoid a stalled process.

Once the reflection adjustment reaches the desired five reflection zeros without an unreasonable bandwidth widening in transmission, the response depicted in figure 6.e is obtained. This response is shown overlapped with *a family scanning* dotted circuital optimization mask. It aims at observing the natural evolution of the algorithm in order to locate filters within the same family of solutions. To this end all dots present unit weight: $\alpha_{1\ldots6,} = 1,\ \beta_{1\ldots11} = 1$.

Upon completion of the previous mask, the filtering response is represented in 6.f. It is considered a response close enough to the ideal objective circuital response as to put an end to the iterative optimization process of the third stage.

4.4. Fourth stage

This is the last stage in which the optimization process is involved, where the whole filtering structure is considered (see figure 3.d). In this case natural units are used to optimize the response, with unitary weights in both transmission and reflection (α_i,β_i=1). Although this stage involves the same number of design parameters as in a direct global strategy (i.e. h_f, dc_1, dc_2, dc_3, L_{i1}, L_{i2} and L_{i3} due to the symmetry of the structure), those variables which were involved in the foregoing stage already have a value very close to the final optimal solution. This was the goal of previous stages.

It is important to mention that this stage differs from the preceding ones in the sense that whereas the previous stages sought the specific number of reflection zeros, at this stage this is not mandatory, as the aim of the whole filter design process from the industry side may be formulated in terms of a mask of reflection and rejection, and not to the aforementioned zeros. The visibility of the zeros becomes therefore a secondary objective. Notwithstanding, in this case study the implemented mask was point-based and the optimization process led to a response with six reflection zeros (figure 7.a) with a very good matching with the circuit response. However, it would have been perfectly correct to use a level-based mask at this stage instead.

At this point, it is important to mention that the electromagnetic simulation software used throughout the design process used settings oriented to the attainment of fast but relatively imprecise results. The underlying reason of this decision is that it was considered preferable to allow the optimization process to make more evaluations and therefore grant the possibility of finding out the behavior of the selected mask to correct it if needed.

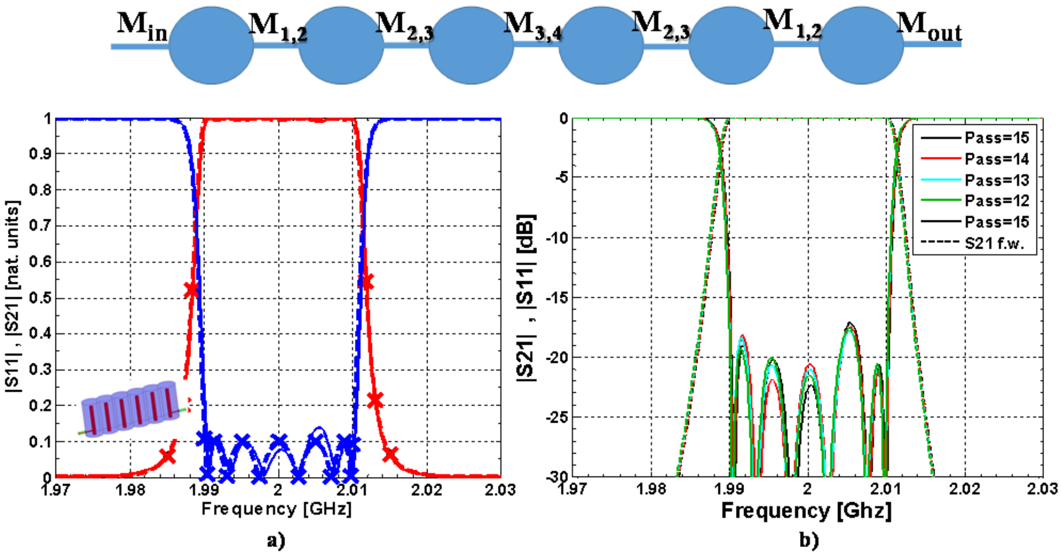


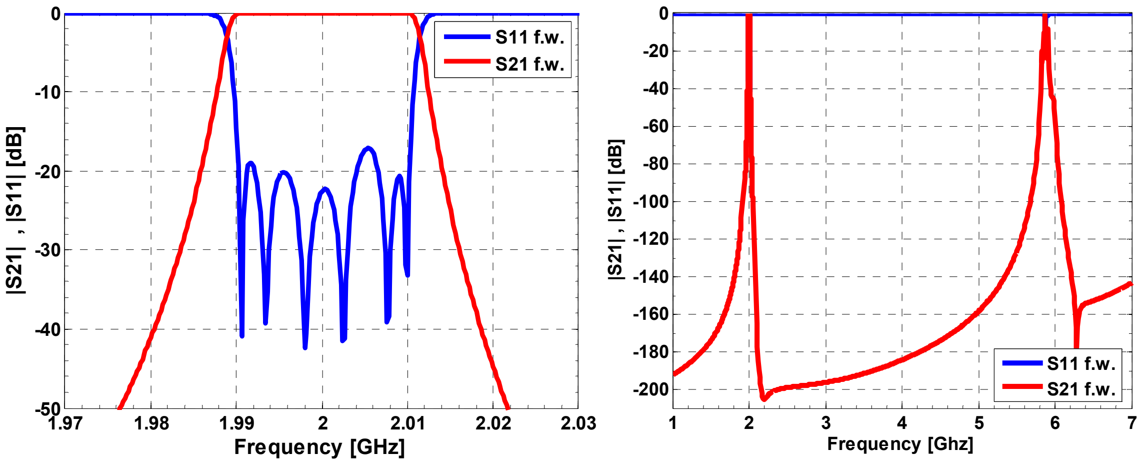
Figure 7. a) End of fourth stage b) Convergence of the FEM simulation for the final filter, where each pass has associated a finer mesh.

However, any final design must guarantee that the simulated response matches with reality. Accordingly, studying the convergence of the designed structure is a must. Since the FEM algorithm was used, this is directly translated as an increased number of meshing passes. Figure 7.b. shows the aforementioned convergence process. Table 1 gathers the final physical parameters of the designed filter (as defined in figure 2), and the final response is depicted in figures 8.a (narrowband response) and 8.b (wideband response, showing first spurious band at approximately $3f_0$=6 GHz, typical of combline filters [2]).

5. CONCLUSION

Filter design method based on stages has been used throughout this work. A sixth-order cavity combline bandpass filter was designed in four stages. Each of them used the preceding one as the starting point of a manual-coarse adjustment, after which the optimization tool is used as a process of refinement to achieve the desired partial response.

The stage approach offers one main benefit: these designs show lower uncertainty levels in terms of the physical parameters of the structure as opposed to designs that take into account the full structure from the very beginning. In this way a coarse adjustment is more easily obtained as a good starting point for optimization, which in turn translates into the optimization tool being closer to the optimal solution. This does not only mean a lower number of iterations, but also that a local-deterministic algorithm suffices to obtain the desired response. This process may result in even more benefits for filters with more complex coupling arrangements.



a) b)

Figure 8. a) Filter response of the final structure obtained with the proposed optimization strategy (dimensions in Table 1); b) Wideband response of the filter.

[mm]												
L_{cav}	R_e	R_i	h_f	L_{i1},L_{i6}	L_{i2},L_{i5}	L_{i3},L_{i4}	dc_1,dc_5	dc_2,dc_4	dc_3	R_{ci}	R_{ce}	ε_{rcoax}
40.2	10	2	1.901	34.397	34.147	34.172	17.150	17.850	17.935	0.638	2.03	1.88

Table 1. Final physical design parameters as defined in figure 2 for the microwave combline filter used to validate the optimization approach.

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