# FAST GLOBAL OPTIMIZATION OF MICROWAVE FILTERS

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## ABSTRACT

A new technique for the fast optimization of microwave filters is presented and applied to the design of a Ku Band seventh order interdigital coaxial filter. The new optimization algorithm has a global nature and does not require the preparation of a surrogate model or any additional work besides the creation of a parametric 3D model of the filter structure. The precise position of the current design within the design space is in fact retrieved in an automatic way exploiting a new symmetric configuration of the ideal circuit and the unique capabilities of the EmCAD modeler.

Key words: Filter Design; Filter Optimization; Filter Tuning; Electromagnetic Solver; Equivalent Circuit;.

## 1. INTRODUCTION

It is a common practice to start a filter design with the synthesis of a lumped circuit that represents an idealization of the actual microwave component. The lumped circuit can be analysed in a short time using closed formulas so that it is very helpful in the preliminary trade-offs aimed to the definition of the main design properties (filter order and allocation of transmission zeros).

One of the most challenging part of the design is nevertheless the tuning of the microwave structure which implements the ideal circuit in the selected technology (such as microstrip, waveguide or anything else). The difficulty of this task is due to the long computation times required for an accurate electromagnetic simulation and to the large number of optimization variables.

The direct application of a generic optimization algorithm is penalized by prohibitive computation times. In addition the fastest optimization algorithms have a local nature and are prone to be trapped in a local minimum so that the convergence to the unique global solution is not always granted.

These challenges has been addressed by several works published by the microwave filter community. For brevity I will just mention the space mapping technique which was first conceived by J.Bandler ([1], [2]) and makes use of a functional mapping between the accurate full wave model and a coarse (or "surrogate") model in order to reduce the number of the accurate (and heavy) simulations. This transformation is not know in advance and is approximated in the course of the optimization process. Space mapping may yield a satisfactory designs after a few fine model evaluations; however, its performance depends heavily on the quality of the coarse model considered.

This paper presents a new technique which makes use of a "surrogate model" which has the same topology as the ideal filter circuit. By exploiting the unique characteristics of the EmCAD modeler this technique allows a fast (almost immediate) computation of the equivalent circuit associated with the given geometrical variables.

For a better clarity the new technique is described with reference to the design of a specific coaxial filter whose requirements are given in the next section.

## 2. FILTER REQUIREMENTS AND THE SYMMETRIC IDEAL CIRCUIT

The main requirements for the design of the coaxial filter are reported in table 1. The initial trade-offs have shown that these requirements can be met using the ideal resonator circuit of figure 1 which is characterized by a couple of transmission zeros in the proximity of the upper edge.

| | |
|---|---|
| Frequency Bandwidth | 12–12.75 GHz |
| Return loss | $< -20$ dB GHz |
| Out of Band Rejection | $< -70$ dB above 13.2 GHz |

Table 1: Filter requirements

The ideal circuit of figure 1 belongs to a more general class of circuits which are characterized by a symmetric folded layout and make use of shunt capacitors and mutual inductances in the transversal branches and of ideal inverters in the longitudinal branches.

It has been verified that this class of circuits can generate any symmetric filter response with the only limitation that the number of transmission zeros must be lower than the number of reflection zeros (one transmission zeros must be at $\omega = \infty$). An automatic procedure was indeed defined and implemented as a Mupad script for the synthesis of a general symmetric folded circuit. This procedure starts from the specification of a rational function ($D(\omega) = S_{11}(\omega)/S_{12}(\omega)$) which uniquely defines the desired frequency response.

The rational function $D(\omega)$ is defined starting from the filter order, the return loss requirement and the allocation of transmission zeros. This is done using an other automatic procedure that is based on a technique published in [3].

Only one transversal branch is included in the ideal circuit associated with the considered coaxial filter. This branch is responsible of the generation of the couple of transmission zeros.

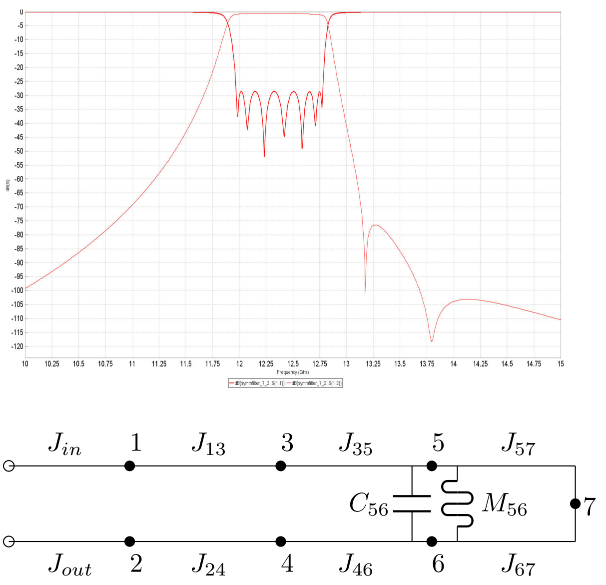


Figure 1: Seventh order ideal resonator circuit and related frequency response

The symmetry constraint is applied to filter geometry and consequently to the scattering matrix ($S_{11} = S_{22}$ in amplitude and phase). This constraint does'nt affect the shape of the frequency response which, as it happens in the present design, may be asymmetric with respect to the central frequency.

It can be verified that the geometrical symmetry leads to a symmetry, about the imaginary axis of Laplace plane, of the patterns of the transmission and reflection zeros. The pattern symmetry may be assured by assuming that that the rational function $D(\omega)$ is characterized by real coefficients. Real polynomia are indeed characterized by complex conjugate (or real) zeros and the conjugation of the $\omega$ variable is equivalent to a reflection about the imaginary axis of the $s = j\omega$ variable.

The geometrical symmetry is preserved when the ideal circuit is converted into the microwave structure and it can be verified that also in this more general case it leads to a symmetry of the zeros patterns about the imaginary axis of Laplace plane. Thanks to this property the transmission and reflection zeros associated with the actual microwave structure define a new real rational function $D'(\omega)$.

The function $D'(\omega)$ can be used to synthesize a new equivalent circuit which has the same topology of the ideal circuit but represents the frequency response of the current (not yet optimized) microwave structure. The numerical parameters (lumped elements) associated with the two circuits are not equal and this difference is directly related to the geometrical corrections which are needed to tune the filter.

We may then conclude that the knowledge of the symmetrical zeros patterns associated with the microwave structure allows a precise diagnosis of the current status of the tuning process. This is an essential prerequisite for the definition of an efficient optimization strategy.

## 3. THE EMCAD TOOL

Even if the ideal transmission and reflection zeros are typically confined on the imaginary axis of the Laplace plane (real frequencies), the zeros associated with a perturbed (but still symmetrical) configuration are not subject to the same condition.

The commercial electromagnetic simulators are based on numerical methods which may be defined in the frequency or in the time domain. In both cases they are not well suited to compute zeros or poles which may lay in a generic position of the Laplace plane. This problem may instead be solved using "EmCAD" ([4]) which is a proprietary Electromagnetic modeler based on a new numerical method.

Differently from most other full wave solvers, EmCAD does not directly compute the electrical response but defines an equivalent circuit that is representative of electromagnetic behaviour of the physical device (both in the frequency and in time domain). Sometimes a solver which follows this approach (an other example is given by the PEEC method [5]) is said to be working in the "circuital domain".

The main advantage of this approach lies in the higher flexibility which is offered by a circuital model with respect to the response curves. The equivalent circuit generated by the EmCAD code is composed of standard lumped elements (such as resistors, capacitors, inductors, and ideal transformers) and may be exported in a standard "spice" format. This file may be easily imported in most circuit simulators and may, in example, be inserted in a larger circuit which includes active parts and is subjected to system analyses (eye diagrams, bit error rates..). The availability of a circuital model brings substantial advantages also in the computation of the transmission and reflection zeros because, for a linear circuit, this problem may be formulated as a linear eigenvalue problem.

The geometrical structure of the microwave circuit is defined using a commercial CAD system and subsequently imported into the EmCAD environment using the neutral “step“ format. In order to exploit the intrinsic parallelism of the EmCAD code a complex structure should be defined as an assembly of simpler parts (or “components“ in the EmCAD language). The coaxial filter which is the object of the present design were defined as an assembly of the seven resonators (see fig. 2).

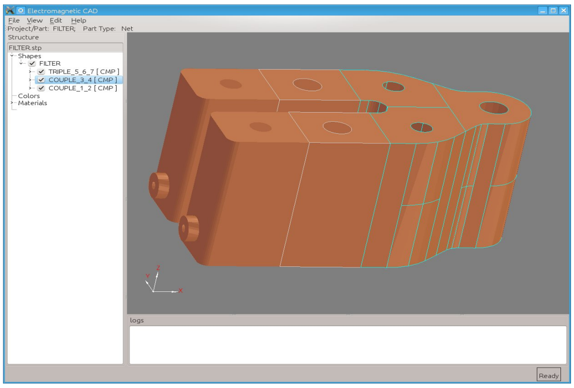


Figure 2: Coaxial filter imported in EmCAD

Each component has to be further subdivided in a set of “small“ simply connected volumes. This partition is defined by drawing (inside of the CAD environment) a set of cutting surfaces. These surfaces must be included in the step file transferred into the EmCAD software and must be tagged with names starting with the “SPLIT“ substring so that they can be distinguished from other kind of surfaces. Other surfaces are in example used to define boundary conditions and waveguide ports and in this cases they are tagged with names starting with the “BC“, “WG“ substrings.

After having imported the step file the EmCAD user may assign the relevant electrical properties to the geometrical entities (dielectric properties, boundary conditions, port modes, frequency band . . . ). Then it is possible to execute the “Decompose“ command which splits all the solid parts (different dielectrics) intercepted by the cutting surfaces. The cell boundaries are finally triangulated according to the specified mesh size using the “Mesh“ command. These operations are applied to the assembly and are executed in parallel for all the subcomponents. Fig 3 shows the resulting decomposition and surface mesh associated with the first resonator of the coaxial filter.

The equivalent circuit generated by EmCAD has a hierarchical structure and is built from the bottom up starting with the circuits associated with the meshed cells.

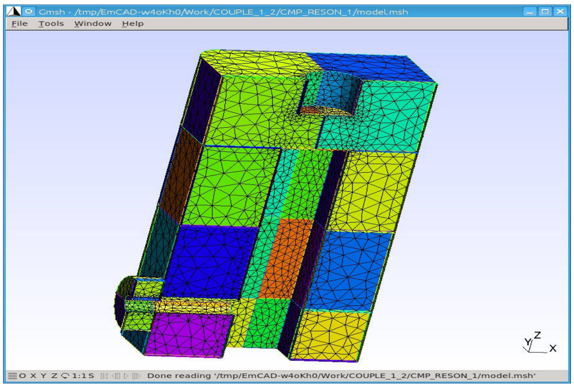


Figure 3: Domain decomposition and meshing of first resonator

The cell circuits are computed by means of a new numerical method which involves a sequence of electrostatic and magnetostatic problems. These are solved with the boundary element method (BEM) with reference to a set of currents (electric and magnetic) localized on the meshed cell boundaries.

The equivalent circuit associated with a given cell represents its electromagnetic response with respect to a complete set of excitations (or ports) localized on the cell boundary. The number of ports is two times the number of mesh points. This circuit includes also a number of internal nodes which is, more or less, comparable with the number of ports.

The circuits associated with different cells are connected together to form the equivalent circuit associated with a given component (a resonator in our case). Depending on the mesh size, the component circuit may contain a large number of lumped elements so that it is convenient to apply a model order reduction before using it in the global circuit.

The Model Order Reduction is automatically applied by EmCAD and does not require any user intervention apart of possible changes of the default settings. This reduction is based on a standard technique [6] that involves the projection of the circuit variables on a Krylov subspace. The result is a compact model which is representative of the electrical response of the given component. The reduction preserves all the fundamental properties (passivity, causality, reciprocity) of the original circuit without any sensible degradation in the accuracy of the frequncy response.

A second model order reduction is applied to the global circuit which is composed of the reduced circuits associated with the components. The final result is a compact circuit that represents the electrical response of the complete microwave structure (coaxial filter in our case). This circuit can not be directly compared with the ideal circuit of figure 1 because of its different topology. A simple zero-pole analysis is anyway sufficient to compute the transmission/reflection zeros and these data can be used to drive the synthesis procedure mentioned in the previuos section.

The EmCAD environment includes a set of commands, organized in a graphical user interface, which may be executed after the model generation (activated by “Modelize“ command) in order to analyse, plot and export some relevant data. In particular it is possible to:

(a) Analyse and plot the frequency response of the microwave structure.

(b) Compute and plot the transmission and reflection zeros in a rectangular window of the Laplace plane.

(c) Generate and export the symmetric equivalent circuit (computed from the zeros of point (b)) characterized by the topology of fig 1. This circuit may be directly compared with the ideal circuit to drive the next geometrical correction.

(d) Analyse and plot the frequency response of the equivalent circuit generated at point (c). This response should be very close to the actual filter response computed at point (a).

After having applied the geometrical variations and regenerated the step file, the “Reload“ command of the EmCAD environment updates the geometry (by preserving all the assigned electrical properties), the cell decomposition and the mesh. Subsequently the user may use the “Update“ command in order to regenerate the electrical model and to update the electrical analyses.

## 4. IMPLEMENTATION AND TUNING OF THE MICROWAVE FILTER

The ideal circuit shown in fig. 1 has been implemented using the interdigital coaxial resonator technology. The coaxial resonators tagged with numbers 1, 2, 5, 6 are oriented in one (up) direction while the other resonators 3, 5, 7 are oriented in the opposite (down) direction. With an odd number of resonators (7 in this project) it turns out that the main (in-line) couplings ($J_{13}$, $J_{35}$, $J_{57}$, $J_{67}$, $J_{46}$ $J_{24}$ in the fig. 1) are all of interdigital type and involve opposite oriented resonators. On the other side all the transversal couplings (only $J_{56}$ in the present filter) are of combline type and involve equally oriented resonators.

This is a favourable situation because the interdigital configuraton is better suited to generate the high coupling values associated with the main branches. The combline configuration is instead better suited to provide a separate regulation of the capacitive and inductive parameters associated with the transversal branches. It can be verified that the capacitive and inductive contributes associated with a combline configuration have opposite sign (as required by the ideal design) and that their difference (in absolute value) increases with the capacitive loading of the coaxial resonators. By a proper dimensioning of the copacitive loading and of the distance associated with the resonators 5, 6 it is then possible to have a complete control of the parameters $C_{56}$ and $M_{56}$.

The filter parameters were optimized by iterating the following actions:

1. Reload, Update and Export of the symmetric equivalent circuit.

2. Define the geometrical correction by comparing the updated circuit with its previous version and with the ideal circuit.

3. Apply the change to the parametric CAD model with regeneration of the step file.

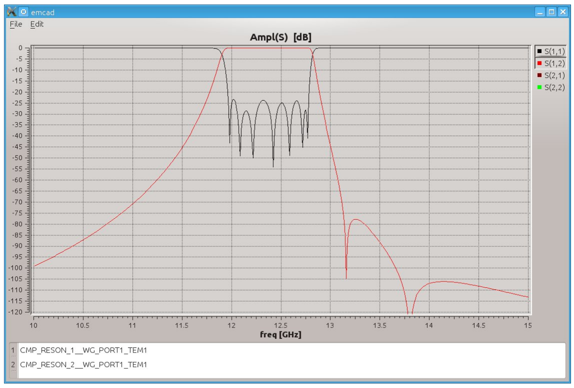


Figure 4: Frequency response computed by EmCAD

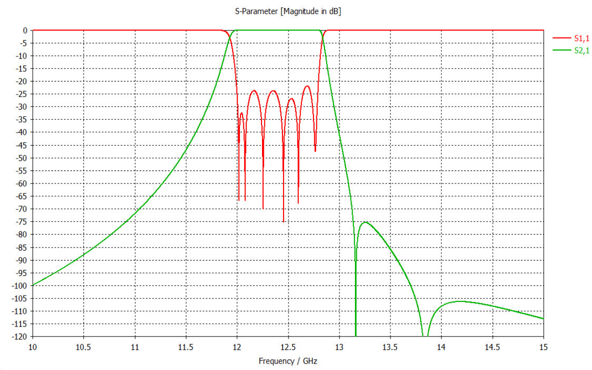


Figure 5: Coaxial filter and frequency response computed by CST

The numerical results have shown that the circuit comparison provides a precise diagnosis of the current status of the filter design at each iteration pass. The convergence criteria was met in a small number of iterations (less then 20) requiring one solver run (less than 30 minutes) per iteration. The frequency response associated with the optimized coaxial filter has been computed using the EmCAD modeler and CST Microwave Studio. The two results are shown in the figures 4 and 5.

## 5. CONCLUSIONS

A new global and fast optimization algorithm has been defined which is characterized by a high robustness (it can't be trapped in a local minimum) and doesn't require a starting point very close to the solution. This algorithm is based on a new procedure for the synthesis of a symmetric folded ideal circuit. The symmetry of this circuit and of the associated microwave structure plays an important role to assure the closure of the optimization loop. The algorithm exploits the unique characteristics of the EmCAD modeler for the computation of the transmission and reflection zeros associated with microwave structure.

The symmetric ideal circuit includes capacitive and inductive elements beside of the (more common) ideal inverters. These additional elements impose certain restrictions in the physical configurations of the resonator coupling structures. In fact it is necessary to assure a separate control of the capacitive and inductive contributes associated with each transversal coupling. The presented design of the interdigital coaxial filter is anyway an example of a possible implementation of the proposed symmetric ideal circuit.

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