Parametric Modeling of the Coupling Parameters of Planar Coupled-Resonator Microwave Filters

Matthias Caenepeel, Fabien Seyfert, Yves Rolain, Martine Olivi

Parametric Modeling of the Coupling Parameters of Planar Coupled-Resonator Microwave Filters

Matthias Caenepeel*†, Fabien Seyfert†, Yves Rolain* and Martine Olivi†
*ELEC, Vrije Universiteit Brussel
Pleinlaan 2, 1050 Brussel, Belgium Email: mcaenepe@vub.ac.be
†APICS, INRIA Sophia Antipolis
2004 Route des Lucioles, 06902 Valbonne, France Email: fabien.seyfert@inria.fr

***Abstract*—The design of planar coupled-resonator microwave filters is widely based on coupling matrix theory. In this framework a coupling matrix is first obtained during the synthesis step. Next this coupling matrix is physically implemented by correctly dimensioning the geometrical parameters of the filter. The implementation step is carried out using simplified empirical design curves relating the coupling coefficients and geometrical parameters. The curves typically only provide initial values and EM optimization is often needed such that the filter response meets the specifications. This paper proposes to extract parametric models that relate the filters design parameters directly to the coupling parameters. The advantage of such models is that they allow to tune the filter in a numerically cheap way and that they provide physical insight in the filters behavior. This paper explains how such models can be extracted from EM simulations and illustrates the technique for the design of an 8 pole cascaded quadruplet filter in a microstrip technology.**

I. Introduction

Coupling matrix theory is widely used to design narrow-band bandpass microwave filters [1], [2] in which the filter is modeled as a low-pass coupled resonator circuit (Fig. 1) [3]. The design process begins therefore by the derivation of a filtering characteristic meeting the filtering specifications. In a second step this characteristic is realized by a circuit. Next the circuit elements (coupling parameters) must be implemented physically by correctly dimensioning the geometrical parameters of the filter. An initial dimensioning of the filter is carried out by means of simplified empirical design curves relating the coupling parameters and geometrical parameters of the filter [4]. These curves however typically do not take into account more complex interactions, such as loading effects of the resonators by the couplings, which require that the initial values must be optimized to meet the filter specifications.
Several electomagnetic (EM) optimization techniques exist in the literature [2]. Although these techniques prove to be successful, there are still some disadvantages. The computation time grows rapidly with the complexity of the design (number of geometrical parameters). When the filter specifications change even slightly, the whole optimization process must be relaunched. Moreover the optimization process does not provide any physical insight in the filters behavior.
Literature shows that the coupling parameters are smooth functions of the controlling geometrical parameters [4], [5]. Therefore we propose to approximate this relation as a quadratic multivariate polynomial. The multivariate character stems from the fact that we also take into account several parameters to model second order effects such as the loading of the resonators. The main advantage is that these models are numerically cheap to evaluate and provide physical insight in the filters behavior. Moreover they can be re-used in various design scenarios. This paper explains how such parametric models can be extracted from EM simulations.
A crucial step in the modeling process, is the extraction of the coupling parameters from the simulated scattering data (S-parameters).

State-of-the-art gradient-based parameter extraction methods optimize the generalized low-pass network such that the networks frequency response meets the measured or simulated response [6], [7]. In the case where multiple solutions are possible, these methods do not necessarily converge to the implemented circuit. Section II shortly describes a three stage extraction process that overcomes this drawback. The S-parameters and network parameters are related as follows [8] $S(s) = I + C(sI - A)^{-1}C^t$ with

$$C = \begin{bmatrix} i\sqrt{2R_{in}} & 0 & \dots & 0 \\ 0 & \dots & 0 & i\sqrt{2R_{out}} \end{bmatrix}, \quad (1)$$

$$A = -R - iM. \quad (2)$$

The first step identifies a rational matrix from the simulated S-parameters [8]. The second step finds all possible circuital realizations of the previously computed rational approximation with a specified coupling topology. The third step finally deciphers the physically implemented matrix.
Section III describes how, given the physical coupling parameters, the quadratic multivariate polynomials are estimated in a least-squares sense. Eventually the modeling technique is illustrated for a design of an 8 pole cascaded quadruplet filter in microstrip technology (Fig.2). The design example shows that the models can be used to improve the filter response drastically.

II. Coupling Parameter Extraction

This section describes the three stage parameter extraction procedure. First a canonical solution is extracted. Next all possible solutions corresponding to the desired topology are identified. Finally the physically implemented coupling matrix is identified among these solutions using prior knowledge. A more detailed explanation can be found in [9].
The first step identifies a rational matrix from the simulated

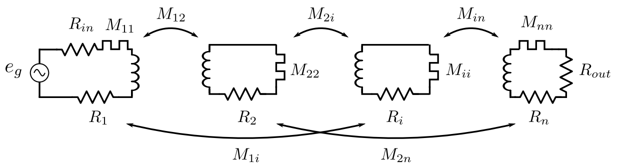

Fig. 1: Low-pass prototype network model for a general cross-coupled resonator filter.

S-parameters. The scattering data is first transformed to the low-pass domain. Next a rational common denominator matrix is identified using the toolbox PRESTO-HF [10] . The order of the common denominator n is chosen to be equal to the number of resonators. The rational matrix is then transformed into the canonical arrow form of the coupling matrix.

The second step finds all possible realizations for the given rational matrix corresponding to a given topology. This topology corresponds to the topology used during the synthesis step. It is however possible that for certain geometrical values, the corresponding S-parameters can not be realized with the ideal topology. E.g. the response is asymmetric while the topology is only able to realize symmetric responses. Such a situation might occur when frequency offsets and/or extra couplings are present in the physical structure. To handle these situations the allowable topology is extended to a topology that is close to the original topology but still allows to capture these effects. This corresponds to expanding the class of realizable responses of the filter. Next the arrow form obtained during step one is transformed to the new topology using the toolbox DEDALE-HF [11]. The only drawback of this extended topology is that it concentrates the extra couplings at fixed positions in the matrix, while physically they might occur somewhere else. To compensate for this unwanted effect, the solutions found by DEDALE-HF are optimized by means of similarity transformations on the coupling matrix. This optimization process minimizes the influence of the extra couplings by redistributing them over the whole matrix. The influence of the extra couplings is expressed by a relative measure c:

$$c = \frac{\Sigma(M^{extra})^2}{\Sigma(M^{all})^2} \tag{3}$$

which is the sum of squares of the extra couplings (M^{extra}) over the sum of the squares of all the couplings (M^{all}).

During the last step of the process, the physically implemented coupling matrix is estimated among the solutions found during step 2. The choice of this matrix is based on some physical assumptions. First of all we assume that the couplings present in the original topology are dominant in the implemented filter. Therefore only those solutions for which c is sufficiently small are considered. Since we use the extraction method in a design context, we assume that the implemented couplings are close to the ideal ones found during the synthesis step. Therefore the solutions for which the 2-norm of the difference to the ideal coupling matrix is minimal is chosen. To model the couplings as a function of the geometrical parameters, the filter is simulated for several geometrical values. This information allows to check whether the choice of the physical matrix is consistent with the geometry. E.g. when the spacing between resonator i and k is varied, this should mainly affect the coupling M_{ik}. If this is not the case, the solution that is coherent with the geometric variation, is chosen instead.

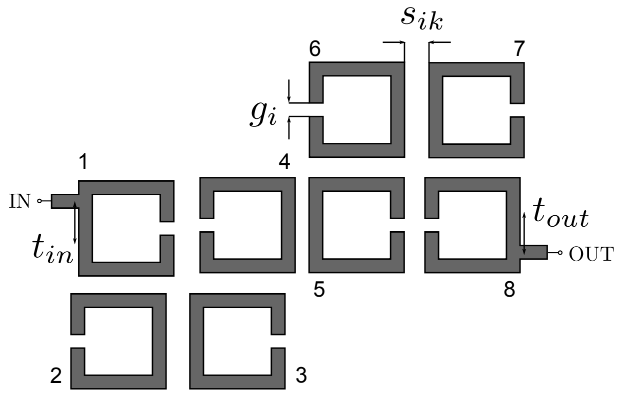

Fig. 2: Top-view of a square open-loop resonator cascaded quadruplet filter and the design parameters s_{ik}, g_i, t_{in} and t_{out}.

III. Multivariate Quadratic Approximation

The design curves that are available in the literature show that the behavior of coupling parameters as a function of the geometrical parameters is smooth [4], [5]. Therefore we propose to model the coupling parameters using multivariate polynomials of a maximal degree of 2. Since the process described in section II, extracts the physical coupling matrix, it is possible to relate a coupling parameter directly to a set of geometrical parameters.

We illustrate this with the example of 2 coupled resonators. It is known that the coupling between 2 resonators depends strongly on the spacing between the resonators, but is also affected by a possible offset introduced by spacings between other adjacent resonators (Fig.3). In this case we propose to use the following model:

$$M_{ik} = a_1 s_{ik}^2 + b_1 s_{ik} + b_2 d + c_1 \tag{4}$$

where s_{ik} is the spacing between the resonators and d represents the offset. In this case 4 coefficients a_1, b_1, b_2 and c_1 must be estimated. This requires at least 4 different EM simulations. The mesh that is used for the different simulations however might differ slightly since it depends on the geometry. This difference together with the error norm between the rational model and the EM simulation used during the extraction step, introduce an error on the extracted coupling matrices. To avoid that the parametric model of the coupling parameter would model these effects as well, we propose to use at least 2 times more simulations than what is minimally needed to estimate the coefficients.

The geometrical values for which the filter must be simulated are selected as follows. First the initial values for the geometrical parameters are determined using the design curves. Next the physical coupling matrix for this structure is extracted. This coupling matrix gives an idea of the distance between the initial design and the ideal design. This allows to determine a validity interval around each design parameter. Values for each geometrical parameter are then randomly generated

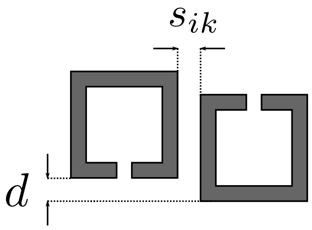

Fig. 3: Top-view of 2 coupled resonators, where s_{ik} is the spacing between them and d is a possible offset.

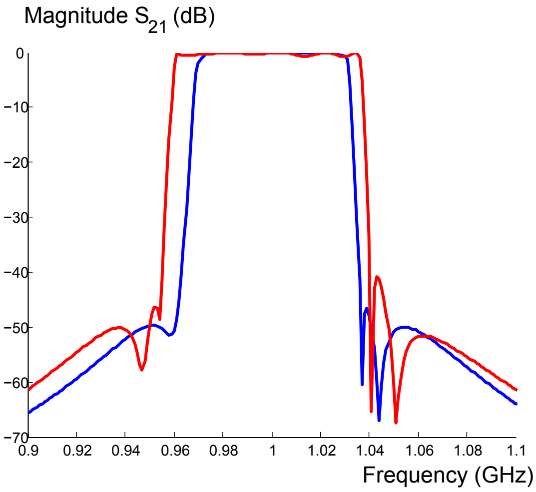

Fig. 4: Magnitude of S_{21} for the initial (red) and final (blue) design.

within this interval. The number of values corresponds to the proposed number of simulations needed to estimate the parametric models. The filter is simulated for all these sets of values. Once the EM simulations are gathered, the coupling parameters are extracted using the method described in section II. The couplings together with the geometrical parameters are then used to estimate a parametric model for each coupling parameter in least-squares sense.

IV. Example

The design of an 8-pole cascaded quadruplet microstrip filter consisting of square open-loop resonators (Fig.2) is used to illustrate the proposed method. The filter is designed for a center frequency f_c of 1 GHz and fractional bandwidth FBW of 0.06. The ideal coupling matrix is synthesized using DEDALE-HF. The synthesis step yields 2 possible solutions among which one is chosen. The filter is implemented in a RT/duroid substrate with a relative permittivity 10.2. The initial dimensions of the filter are obtained using empirical formulae derived for the coupling coefficients between square open-loop resonators [12]. The filter is simulated using ADS Momentum 2014 [13]. Fig. 4 and 5 show that the responses can clearly be improved with respect to center frequency, insertion loss and bandwidth.

There are three types of coupling parameters that potentially need to be tuned and thus modeled:

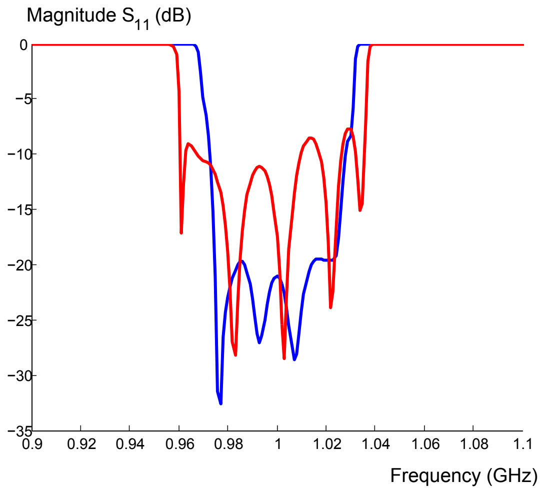

Fig. 5: Magnitude of S_{11} for the initial (red) and final (blue) design.

- Inter-resonator couplings M_{ik} where $i \neq k$
- Center frequency offsets M_{kk}
- Normalized input/output impedances R_1 and R_2 respectively

It is well known that inter-resonator couplings mainly depend on the spacing between the resonators. Spacings between other resonators can introduce an extra offset (Fig.3). E.g. the coupling between resonator 1 and 2 mainly depends on the distance s_{12}. The spacing between resonator 1 and 4, labeled s_{14} and the spacing between 2 and 3, labeled s_{23} introduce an offset $\frac{|s_{14}-s_{23}|}{2}$. Thus we can model this coupling as:

$$M_{12} = a_1 s_{12}^2 + b_1 s_{12} + b_2\left(\frac{|s_{14} - s_{23}|}{2}\right) + c_1 \tag{5}$$

The same reasoning can be repeated for the other inter-resonator couplings.

The diagonal elements M_{kk} express the difference between the center frequency of the filter and the resonance frequency f_k of resonator k. f_k is directly related to the length of the resonator and thus to g_k, but also depends on the loading of the resonator influences f_k. This loading is modeled by means of the distances between the neighboring resonators. Therefore we propose as a model:

$$M_{kk} = a_1 g_k^2 + b_1 g_k + b_2 s_{k-1,k} + b_3 s_{k,k+1} + b_1 \tag{6}$$

if $k \neq 1, n$ and

$$M_{kk} = a_1 g_k^2 + b_1 g_k + b_2 s_{k-1,k} + b_3 s_{k,k+1} + b_4 t_{in/out} + c_1 \tag{7}$$

if $k = 1$ or n. The normalized input and output impedances mainly depend on the position of the input and output feeding lines. The length of the lines however also has an effect. Therefore we propose a model:

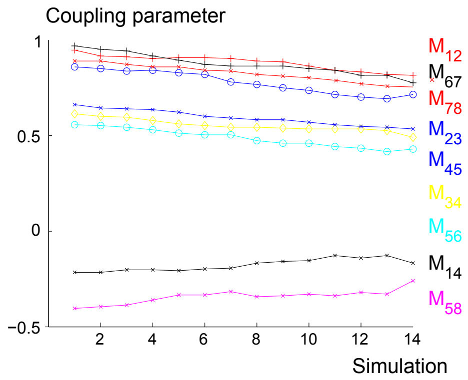

Fig. 6: The extracted inter-resonator couplings for each simulation.

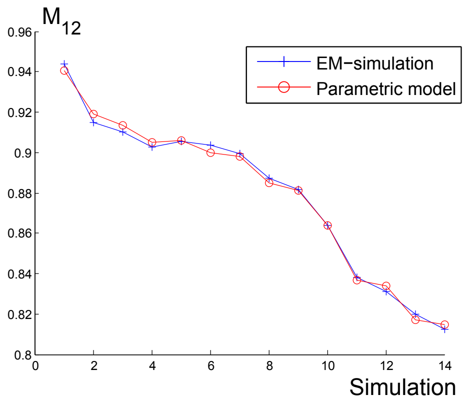

Fig. 7: Comparison between the coupling parameters extracted from the EM simulations (+- blue) and result of the parametric model (o- red).

$$R_1 = a_1 t_{in}^2 + b_1 t_{in} + b_2 g_1 + c_1 \quad (8)$$

$$R_2 = a_1 t_{out}^2 + b_1 t_{out} + b_2 g_n + c_1 \quad (9)$$

This reasoning shows that the most complicated model requires the estimation of 6 coefficients. We propose to perform 14 EM simulations to estimate them. Since the coupling parameters are not too far from the ideal ones, we propose to simulate the filters for values in an intervals varying from 0.3 up to 0.5 mm for the design parameters s_{ik}, since the offset from f_c are also not too large we use the same intervals for g_k. For t_{in} and t_{out} we take an interval of 0.5 mm.

After the EM simulations are gathered, the coupling matrices are extracted using the method described in section II. Fig. 6 shows the extracted inter-resonator couplings for each simulation. Eventually the simulations are used to extract the parametric models given in equations 5-9. Fig. 7 shows the result of the model for M_{12} for all of the simulations. It shows that there is model error, which is expected due to simulation meshing and parameter extraction errors.

Once the parametric models are extracted they can be used to fine-tune the filter. The models form a set of non-linear equations. This set is solved in Matlab using the function $fminunc$. The filter is next re-simulated for the found geometrical parameters. The result is shown in Fig. 4 and 5. The response can still be improved, but remark that only 14 EM simulations were required to tune a filter with 19 design parameters.

V. Conclusion

This paper introduces parametric models that relate the coupling matrix parameters to the design parameters of the filter. The advantage of the models is that they are cheap to evaluate and allow to improve the filters response in a numerically cheap way. We explain how the models can be extracted using EM simulations. Moreover we illustrate the utility of the models with a design example. The design example shows that the models allow to improve the filters response drastically using only 14 EM simulations.

This work is sponsored by the Vrije Universiteit Brussel, dept. ELEC, Pleinlaan 2, 1050 Brussel Belgium, INRIA Sophia-Antipolis, Fund for Scientific Research (FWO-Vlaanderen), the Flemish Government (Methusalem), the Belgian Government (IUAP-VII) and the Strategic Research Program of the VUB (SRP-19).

References

[1] R. J. Cameron, “General coupling matrix synthesis methods for chebyshev filtering functions,” *IEEE Transaction on Microwave Theory and Techniques*, vol. 47, no. 4, pp. 433–442, 1999.

[2] R. J. Cameron, C. M. Kudsia, and R. R. Mansour, *Microwave filters for communication systems*. Wiley-Interscience, 2007.

[3] A. Atia and A. Williams, “New types of waveguide bandpass filters for satellite transponders,” *Comsat Tech. Review*, vol. 1, no. 1, pp. 20–43, 1971.

[4] J.-S. G. Hong and M. J. Lancaster, *Microstrip filters for RF/microwave applications*. Wiley-interscience, 2001, vol. 126.

[5] S. Amari, C. LeDrew, and W. Menzel, “Space-mapping optimization of planar coupled-resonator microwave filters,” *Microwave Theory and Techniques, IEEE Transactions on*, vol. 54, no. 5, pp. 2153–2159, 2006.

[6] P. Harscher, R. Vahldieck, and S. Amari, “Automated filter tuning using generalized low-pass prototype networks and gradient-based parameter extraction,” *Microwave Theory and Techniques, IEEE Transactions on*, vol. 49, no. 12, pp. 2532–2538, 2001.

[7] P. Harscher, E. Ofli, R. Vahldieck, and S. Arnari, “Em-simulator based parameter extraction and optimization technique for microwave and millimeter wave filters,” in *Microwave Symposium Digest, 2002 IEEE MTT-S International*, vol. 2. IEEE, 2002, pp. 1113–1116.

[8] M. Olivi, F. Seyfert, and J.-P. Marmorat, “Identification of microwave filters by analytic and rational h2 approximation,” *Automatica*, vol. 49, no. 2, pp. 317–325, 2013.

[9] M. Caenepeel, F. Seyfert, Y. Rolain, and M. Olivi, “Microwave filter design based on coupling topologies with multiple solutions,” *Accepted for publication on IMS 2015*.

[10] “PRESTO-HF : a matlab toolbox dedicated to the identification problem of low pass coupling parameters of band pass microwave filters.” [Online]. Available: https://project.inria.fr/presto-hf/

[11] “DEDALE-HF : a matlab toolbox dedicated to the equivalent network synthesis for microwave filters.” [Online]. Available: http://www-sop.inria.fr/apics/Dedale/

[12] J.-S. Hong and M. J. Lancaster, “Couplings of microstrip square open-loop resonators for cross-coupled planar microwave filters,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 44, no. 11, pp. 2099–2109, 1996.

[13] Agilent Technologies, “Advanced design system,” 2014, santa Rosa, CA.