Full Wave Coupled Resonator Filter Optimization using a Multi-Port Admittance-Matrix

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***Abstract* — A filter optimization strategy based on full wave EM simulations is proposed. With the introduction of additional internal ports in the filter model, the Multi-Port Admittance-Matrix (Y-Matrix) is obtained. The main advantage lies in the fact that the filter's basic parameters, as there are the resonant frequency of each resonator, the coupling coefficients and the external *Q*s are directly accessible through the Multi-Port Y-Matrix. These values are known to give a broad insight into the filter and allow a straightforward optimization procedure to meet the specified data of the synthesis. Furthermore, parasitic effects and design restrictions can be identified and even quantified. Here, an example of a combline filter with a six pole Chebyshev characteristic has been chosen to demonstrate the technique and to verify the method, which can be adapted to other types of filters as well as to other characteristics. Based on this example, a parasitic external coupling was identified and compensated illustrating the advantages of this method.**

***Index Terms* — coupled resonator filter, multi-port, admittance matrix, filter optimization, filter modeling**

I. Introduction

Filter design is a challenging task with different problems to deal with. After the filter characteristic of a coupled resonator filter has been defined the coupling coefficients as well as external *Q*s can be calculated using filter synthesis technique like in [1]. Choosing a particular topology expecting that the values of synthesis can be met by geometrical variations, breaks down the problem to an optimization task. In this paper an optimization strategy is proposed which introduces one additional port for every resonator in the filter and exploits the Multi-Port Y-Matrix to compute the coupling coefficients and the resonators' Eigen frequencies. One main advantage is that the filter can be optimized without the effects of the external ports, which can strongly affect the filter transmission s_{21}, if they are badly matched. Generally, an optimization procedure with the desired goal specified by s_{21} and s_{11} is not very promising for a discrete optimization using an EM simulator. Furthermore, an s_{21} goal function cannot be directly related to dominant geometrical variations, so that all parameters must be optimized simultaneously causing an immense parameter space to deal with.

In [2] an optimization technique has been proposed which is ideally suited for simulation and measurement. The group delay response of the input reflection coefficient can be evaluated so to derive the filter-parameters. While the here proposed method is mainly restricted to EM simulations due to the additional inner ports, it can provide a broader insight into the filter and into the external couplings. In particular, the Multi-Port Y-Matrix provides frequency dependent information on each resonator and the corresponding coupling coefficients. This allows to examine the maximum operating bandwidth of each filter block so to determine a maximum achievable pass-bandwidth of the total filter.

There are different other optimization methods with distinct advantages as well as disadvantages. One method is breaking down a filter model into several sub models. The fast simulation time is at the cost of the complexity of an accurate sub model linking. Another optimization method uses a circuit simulator along with a parameter fitting to extract the filter-parameters. This method requires an either a nearly ideal behavior of the filter or a modified unique circuit model.

The proposed overall EM simulation with the Multi-Port Y-Matrix evaluation of the filter allows taking into account all interacting effects. One optimization goal, like a coupling coefficient can be related to one dominant parameter variation in the filter, which for some filer topologies even allows an almost isolated optimization of each of the parameters.

II. Theory

In Fig. 1 a schematic model of an *N* pole coupled resonator filter is shown. It basically comprises admittance blocks $B_n(\omega)$, which are coupled through admittance inverters $J_{n,n+1}$ [5]. For every resonator one additional port is defined and connected through an ideal transformer. The transformer takes into

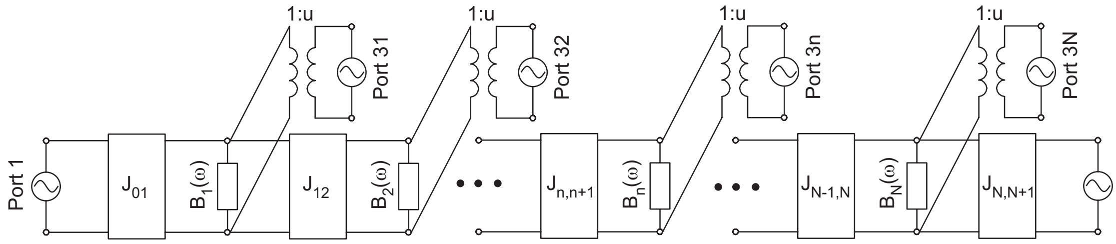

Fig.1: Schematic model of a N pole coupled resonator bandpass filter with two external ports 1 and 2 and N additional internal ports 31 to 3N.

account an admittance transformation due to the port placement at the physical resonator. Based on the (N+2) x (N+2) Y-Matrix:

$$Y = \begin{bmatrix} y_{1,1} & y_{1,31} & y_{1,32} & \cdots & y_{1,2} \\ y_{31,1} & y_{31,31} & & & \vdots \\ y_{32,1} & & \ddots & y_{3(N-1),3N} & y_{3(N-1),2} \\ \vdots & & y_{3N,3(N-1)} & y_{3N,3N} & y_{3N,2} \\ y_{2,1} & \cdots & y_{2,3(N-1)} & y_{2,3N} & y_{2,2} \end{bmatrix} \quad (1)$$

the resonance frequency ω_n of each of the n^{th} resonator is found to be:

$$\mathrm{Im}\{y_{3n,3n}(\omega_n)\} = 0, \quad (2)$$

regardless of the transformation ratio u. The diagonal elements of the Y-Matrix carry the information on the Eigen-frequency of each of the resonator, shorting the adjacent resonators to suppress the coupling and the corresponding frequency shift. With the frequency normalized slope of $B_n(\omega)$,

$$b_n = \frac{f_0}{2}\frac{\partial B_n(\omega)}{\partial \omega} = \frac{f_0}{2}\frac{\partial\, \mathrm{Im}\{y_{3n,3n}(\omega)\}}{\partial \omega}u^2, \quad (3)$$

the coupling coefficients $k_{n,n+1}$ can be extracted from the Y-Matrix elements using the following relation:

$$k_{n,n+1} = \frac{J_{n,n+1}}{\sqrt{b_n b_{n+1}}} = \frac{\mathrm{Im}\{y_{3n,3n+1}(\omega_n)\}}{\sqrt{b_n b_{n+1}}}u^2 \quad (4)$$

The coupling information can be calculated from the non-diagonal elements of the matrix along with the slope of the diagonal matrix elements.
The external Qs are computed in a similar way with

$$Q_{in} = \frac{b_1 G_a}{J_{0,1}^2} \text{ and } Q_{out} = \frac{b_N G_a}{J_{n,n+1}^2} \quad (5)$$

for the input and output port terminated with G_a.
The coupling coefficients and external Qs are independent of the transformation ratio u as long as u is of the same value for all resonators. Here, we can see that the all the admittance transformations cancel out each other, when all the ports are placed at a position with the same transformation ratio.

III. EM SIMULATION

A. Specification

Poles:	6
Center Frequency:	918 MHz
Bandwidth:	20 MHz
Ripple:	0.1dB

B. Model

A combline filter model has been chosen for optimization to meet the filter specification. In Fig. 2 the EM simulation model of a six pole cavity combline filter is depicted. On top of each resonator a dielectric disc is placed to fine tune the resonant frequency by a permittivity variation to model a tuning screw. For the six resonators three permittivity variables have been defined, the two outer discs er1=er6, the second and fifth disc er2=er5 and the third and fourth disc er3=er4, respectively. The finite difference time domain solver (FDTD) Empire [4] has been used to perform the EM simulation of the whole Multi Port Filter Model. The model works on a fixed grid with a constant discretization of 1mm in every direction, generating a 309 x 15 x 61 mesh. The filter model was setup exploiting the symmetrical nature in y-direction using a magnetic wall.

C. Optimization Procedure

Table 1 shows a summary of the overall optimization process. In the column "goal values" the desired coupling coefficients and external Qs from the filter synthesis are given. Different parameters have been grouped and four independent optimization processes have been carried out. In optimization 1, the resonance frequencies have been adjusted by optimizing the permittivity variable er1, er2 and er3. With the proper resonance frequencies the coupling coefficients have been optimized simultaneously with the grouped variables d_{12}, d_{23} and d_{34}, in optimization 2. The variables *port_height*, er1 and d_{12} have been grouped in optimization 3 to adjust the external coupling. Finally in optimization 4, a fine tuning of the resonance frequency has been done to obtain a nearly ideal filter characteristic. The results would have also been satisfactory without this additional post fine tuning.

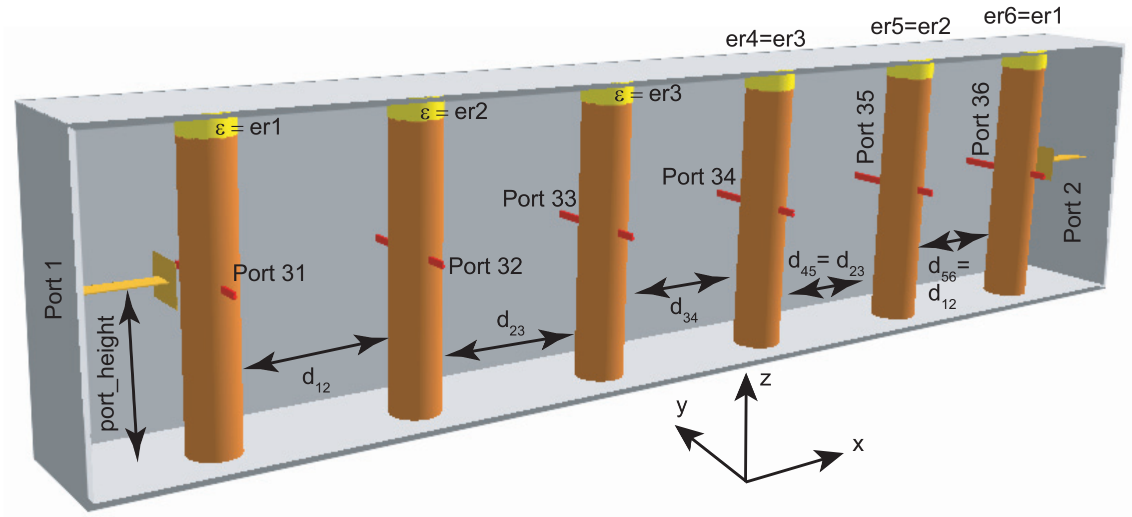

Fig.2: Parameterized EM Model of the combline filter with variables for the optimization process. Filter Specification: *N*=6 poles, bandwidth: 20 MHz, centre frequency: 918 MHz ripple: 0.1dB.

TABLE I
SUMMARY OF OPTIMIZATION

Fixed Parameter	Optimization Par.	Start Values / Steps	Res. Frequency	Optimized Parameters	Optimized Res. Freq.	Goal Values	Opt. Iterations
d12 = d56 = 20mm	er1 = er6	1 / 0.02	f1 = 1082.2 MHz	er1 = 4.42	f1 = 918.05	f1 = 918 MHz	
d23 = d45 = 20mm	er2 = er5	1 / 0.02	f2 = 1117.2 MHz	er2 = 4.76	f2 = 918.08	f2 = 918 MHz	23
d34 = 20mm	er3 = er4	1 / 0.02	f3 = 1117.3 MHz	er2 = 4.76	f3 = 918.03	f3 = 918 MHz	
port_height = 30mm							
			Coupling Coefficient		**Optimized Coupling Coeff.**		
er1 = 4.42	d12	20mm / 1mm	k12 = 4.41e-2	d12 = 30mm	k12 = 1.69e-2	k12 = 1.701e-2	
er2 = 4.76	d23	20mm / 1mm	k23 = 4.47e-2	d23 = 33mm	k23 = 1.28e-2	k23 = 1.282e-2	17
er3 = 4.76	d34	20mm / 1mm	k34 = 4.47e-2	d34 = 33mm	k34 = 1.28e-2	k34 = 1.233e-2	
port_height = 30mm							
			f1 / d12 / Q		**Optimized f1 / d12 / Q**		
d23=33mm	er1	4.42 / 0.05	f1 = 909.2	er1 = 4.12	f1 = 917.7 MHz	f1 = 918 MHz	
d34=33mm	d12	30mm / 1mm	k12 = 1.686e-2	d12 = 30mm	k12 =1.675e-2	k12 =1.701e-2	15
er2=4.76	port_height	30mm / 1mm	Q = 62.9	port_height = 32mm	Q = 54.4	Q = 53.7	
er3=4.76							
			Res. Frequency.		**Optimized Res. Freq.**		
d12=30mm	er1	4.12 / 0.005	f1=917.7 MHz	er1 = 4.110	f1 = 918.08 MHz	f1 = 918 MHz	
d23=33mm	er2	4.76 / 0.005	f2=918.3 MHz	er2 = 4.770	f2 = 917.94 MHz	f2 = 918 MHz	7
d34=33mm	er3	4.76 / 0.005	f3=918.2 MHz	er2 = 4.765	f3 = 918.06 MHz	f3 = 918 MHz	
port_height = 32mm							
Optimized Values:							
er1 = 4.11, er2 = 4.77, er3 =4.765, d12 = 30mm, d23 = 33mm, d34 = 33mm, port_height = 32mm							

C. Results

In Fig. 3 the s_{11} of the ideal filter is plotted and compared to the EM optimized filter, with all additional ports removed. The results show an unreasonable agreement of the two s_{11} curves.

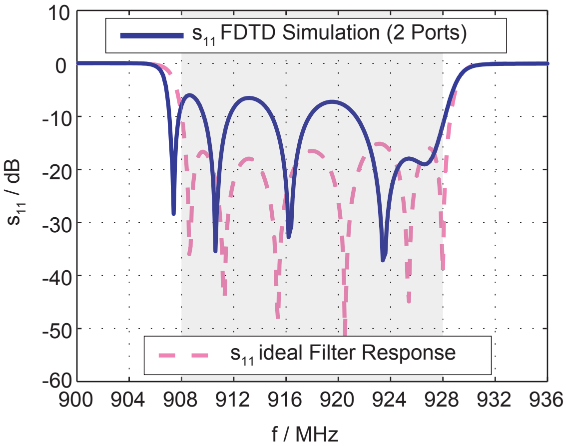

Fig. 3: Discrepancy of the ideal mutual coupled LC filter model (dashed line) and the two-port EM optimized filter model (solid line).

The reason for this discrepancy lies in the parasitic external coupling. The two outer inverters $J_{0,1}$ and $J_{N,N+1}$ (Fig. 1) are found to have non-zero diagonal matrix elements with y_{11} = y_{22} = j6.8mS. Ideally, these values are zero for an ideal admittance inverter.

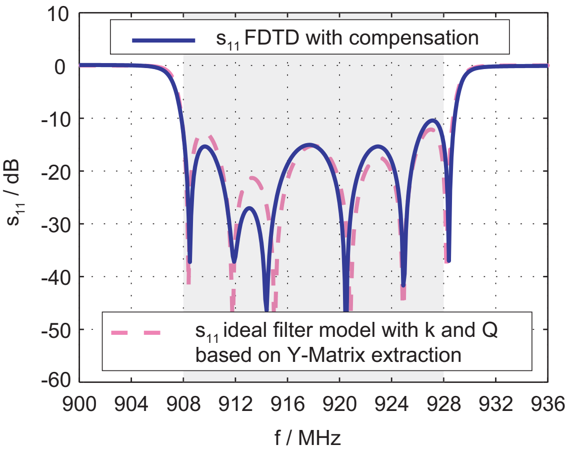

Fig. 4: Verification of the ideal mutual coupled LC filter model with extracted coupling coefficients and external *Q*s from the Y-Matrix (dashed line) and two-port EM filter model with negative parallel capacitance to compensate the parasitic coupling (solid line).

A parallel negative capacitance at port 1 and 2 of C_p=-1.2pF has been introduced in a circuit simulator to compensate the parasitic y_{11} and y_{22} values.

In Fig. 4, the compensated s_{11} of EM model shows a good agreement with the ideal mutual coupled LC filter model, with the coupling coefficients and *Q*s taken from the EM simulated Y-Matrix. Finally, a parallel inductor of L_p = 25nH was placed in the EM model to provide -j6.8mS as a narrow band solution. The overall filter simulation is shown in Fig. 5. Besides, a small increase in ripple to 0.35dB, the filter specifications are perfectly met.

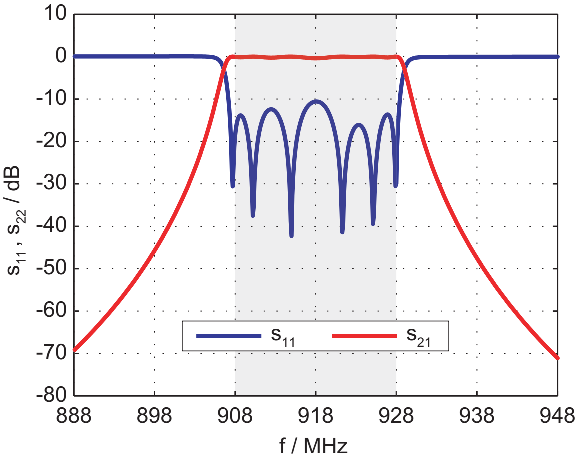

Fig. 5: Overall two-port filter simulation with the parasitic coupling compensated by a parallel inductor at the port.

VI. Conclusion

A novel filter optimization approach has been proposed. The evaluation of the Multi-Port Y-Matrix allows a reliable optimization procedure, providing useful insight into a filter. Furthermore, it was shown the troublesome parts like external couplings, can be identified easily. Our further work includes the optimization of cross coupled filters to obtain an elliptical characteristic along with a more generalized formulation of this method.

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