Design Procedure for Waveguide Filters with Cross-Couplings

Jan Kocbach and Kjetil Folgerø

Nera ASA, Nera Research, N-5020 Bergen, NORWAY. Email: jko@nera.no, kfo@nera.no

Abstract— **A new rigorous systematic design procedure for folded waveguide filters with cross couplings is presented. The procedure is a combination of a circuit model analysis and a full-wave method, and is based on tuning one dimension at a time for simple waveguide structures towards simple tuning goals. Through examples it is shown how the procedure can eliminate the need for global optimization. As a consequence of this process, the time needed for realization of filters of this type is greatly reduced. Examples of filters designed using the described design process are given, including comparison with measurements.**

I. INTRODUCTION

The synthesis of the mechanical dimensions of direct-coupled waveguide filters is well described in the literature (see e.g. [1]-[4]). The corresponding synthesis of multiple coupled resonator filters, like e.g. folded waveguide filters with cross couplings (see Fig. 1), is more complicated, due to the much stronger interaction between the couplings for these types of filters. This makes it difficult to precisely determine the physical dimensions of the coupling structures using the same methods as applied for direct-coupled filters.

One often applied method to overcome this difficulty, is to ignore the interaction between the couplings in the synthesis of the mechanical dimensions [5], leading to poor return loss in the synthesized response. To arrive at the required response, a global full-wave optimization process is applied subsequently [5]. This global optimization process is time-consuming. Therefore, it is advantageous to use a direct synthesis method without optimization whenever this is applicable. An example of such a direct synthesis method has been given in [6] for circular dual-mode filters, in which initial values for the mechanical dimensions are first found by considering each coupling separately, and subsequently these mechanical dimensions are improved by looking at the interactions between some of the couplings.

The aim of this paper is to present a new rigorous systematic design procedure for folded waveguide filters with cross couplings, and to show how this procedure may eliminate the need for global optimization in the design of this type of filters.
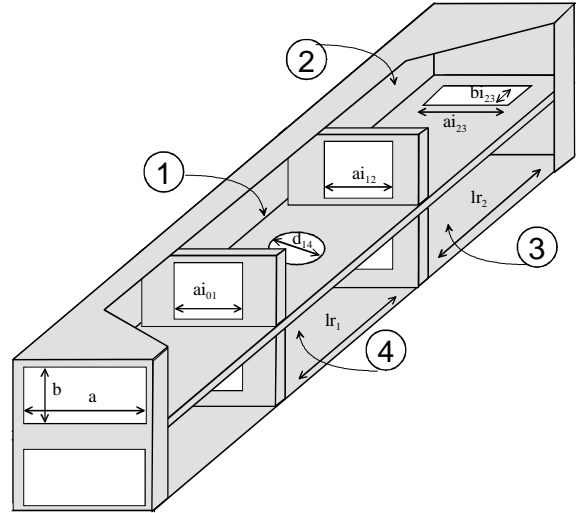

Fig. 1. A 4th order folded waveguide filter with a cross-coupling between cavity 1 and cavity 4, The filter is symmetric around the midplane.

II. METHOD

The suggested design procedure is implemented for symmetrical waveguide filters with cross couplings in the E-plane. As an example, a detailed description for a 4th order cross-coupled filter with cross coupling between the 1st and 4th cavity, as shown in Fig. 1, will be given. Only slight modifications are necessary for higher order filters with more than one cross coupling. The present procedure uses a combination of a circuit model analysis and a full-wave method, where the circuit model acts as a reference.

Fig. 2 shows the circuit model for a nth order cross-coupled filter. Following [7], the loop equation for narrow bandwidths can be written

$$\mathbf{e} = \left(\hat{w}\mathbf{I} + \mathbf{R} + j\mathbf{M}\right)\cdot\mathbf{i} = \mathbf{Z}\cdot\mathbf{i}, \qquad (1)$$

where $\mathbf{e}$ describes the excitation vector ($\mathbf{e}^t$=[1, 0, 0 ... 0]), $\mathbf{i}$ is a vector containing the loop currents of the resonators, $\mathbf{M}$ is the coupling matrix, $\mathbf{I}$ is the identity matrix, and $\mathbf{R}$ is a matrix whose only nonzero elements are $R_{11}=R_{in}$ and $R_{nn}=R_{out}$. Furthermore $\hat{w}$ is the normalized frequency

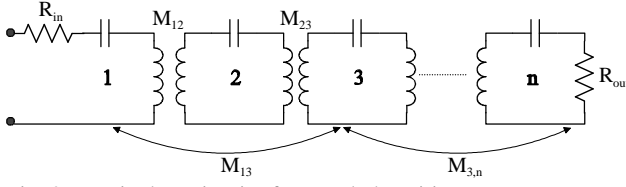$$\hat{w} = j\frac{w_0}{\Delta w}\left(\frac{w}{w_0} - \frac{w_0}{w}\right) \qquad (2)$$

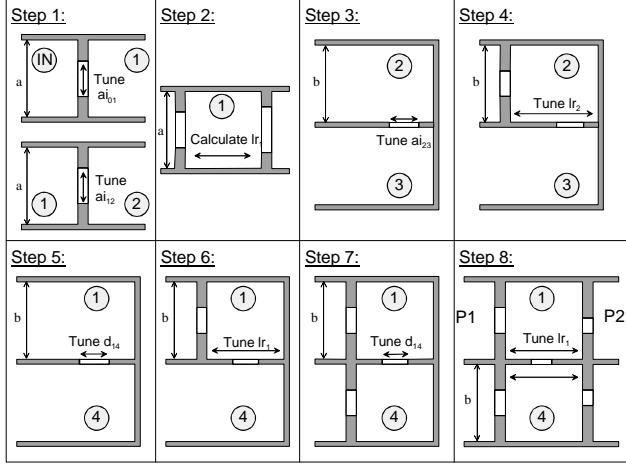Fig. 2. Equivalent circuit of n coupled cavities

Fig. 3. Step-by-step illustration of the design procedure for the filter in Fig. 1. P1 and P2 in step 8 refer to port 1 and 2 of the 4-port, respectively.

where w_0 is the angular center frequency and Δw is the bandwidth. This leads to the following expressions for the s-parameters

$$S_{21} = 2\sqrt{R_{in}R_{out}}\left[\mathbf{Z}^{-1}\right]_{n,1} \tag{3}$$

$$S_{11} = 1 - 2R_{in}\left[\mathbf{Z}^{-1}\right]_{1,1} \tag{4}$$

The realization procedure may be divided into a number of simple steps (see Fig. 3), leading to a design-process well suited for implementation as an automatic procedure on a computer. Each step involves the tuning of one dimension (coupling size or cavity length) in a simple waveguide structure until the simulated s-parameters fit the s-parameters of the representative circuit model. The waveguide structure is kept simple by only including the couplings and resonators that interact strongly, i.e. either a single coupling, a single cavity or two coupled cavities. Simulations are made for a single frequency point in the cases where a coupling is adjusted, and for 10-15 frequency points when a cavity length is adjusted.

A fast convergence for each step is obtained because (i) the simulated substructure is very simple, (ii) only one variable is tuned, (iii) only one or a few frequency points are considered and (iv) the tuning goals are easy to achieve with few iterations.

Below, the design steps are described in detail for the sample case of a 4th order cross-coupled filter. The first four steps are required to realize the folded filter without cross-couplings. This is straightforward, and is done in a similar way as presented in [4]. A more comprehensive procedure is needed to determine the dimensions of the cross coupling and the length of the cavities adjacent to the cross coupling. This is explained in step 5 to 8.

1. Calculate the theoretical $|S_{21}|$ for the input coupling and the coupling between resonators 1 and 2 as reference values. Then simulate a waveguide with a single iris in a full-wave simulator (see step 1 in Fig. 3) at w_0, and change the dimension of the iris until the simulated $|S_{21}|$ equals the reference value.

2. Calculate the length of the first cavity as

$$l_r = \left(p - \frac{1}{2}\left(f_1 + f_2\right)\right)\frac{l_{g0}}{2p} \tag{5}$$

where f_1 and f_2 are the phases of S_{11} for the first and second coupling, respectively, as found in step 1, and l_{g0} is the guide wavelength at w_0. Alternatively, the cavity length may be tuned in using an analogous procedure to the one described in step 4 below.

3. Calculate the theoretical $|S_{21}|$ for the coupling between resonator 2 and 3 as a reference value. Simulate the structure shown in step 3 of Fig. 3 at w_0, and change the size of the hole between cavity 2 and 3 until the simulated $|S_{21}|$ equals the reference value.

4. Simulate cavity number 2 as shown in step 4 of Fig. 3. For $|S_{21}|$, this results in a curve with a single peak at the resonance frequency of the cavity. Adjust the cavity length until the peak is at w_0.

5. Calculate the theoretical $|S_{21}|$ for the coupling between resonator 1 and 4 as a reference value. Simulate the structure shown in step 5 of Fig. 3, in which the coupling between cavity 1 and 2 of the complete filter is replaced by a shorted wall, and the input coupling is removed. Change the size of the hole between cavity 1 and 4 until the simulated $|S_{21}|$ equals the reference value at w_0. This gives a first approximation for the physical dimension of the cross-coupling hole.

6. Simulate cavity 1 with a coupling hole placed in the center of the cavity as shown in step 6 of Fig. 3. Find a new length for cavity 1 by adjusting the cavity length until the peak of $|S_{21}|$ is at w_0. Note that this new cavity length is only applied for the calculation of the cross-coupling hole size in step 7.

7. Calculate the theoretical $|S_{21}|$ for the coupling between resonator 1 and 4 using equation (3) with $M_{12}=M_{23}=M_{34}=0$. Simulate the structure shown in step

7 of Fig. 3 at w_0 with the cavity length for cavity 1 found in step 6, and change the size of the hole between cavity 1 and 4 until the simulated $|S_{21}|$ equals the reference value at w_0. This gives a second approximation for the physical dimension of the cross-coupling hole. Steps 6 and 7 may be repeated to get better approximations for the cross-coupling hole size, but this second approximation has been found to be good enough in the cases considered.

8. Simulate the 4-port in step 8 of Fig. 3. For $|S_{21}|$, this results in a curve with a single peak at the resonance frequency of the cavity. Adjust the length of cavity 1 (and the length of cavity 4, which is equal to the length of cavity 1 due to symmetry) until the peak is at w_0.

Following steps 1 to 8, the physical dimensions of the cross-coupled waveguide filter are found.

Fig. 4. Simulation results for the steps in Fig. 3 for the 4th order cross-coupled filter. These steps result in the overall filter response shown in Fig. 5.

III. RESULTS

The method described has been fully automated using Matlab and the mode-matching/finite element program Wasp-Net [8]. Using this automated process, a number of filters at different frequencies (15 GHz - 43 GHz) have been designed. Results for a four cavity and a six cavity filter are presented below.

A. Four cavity cross-coupled filter

The mechanical dimensions of a four cavity filter with center frequency of 15 GHz and bandwidth of 300 MHz have been synthesized using the described procedure. The prototype filter has normalized input/output resistances $R_{in} = R_{out} = 1.4886$ and coupling matrix

$$M = \begin{bmatrix} 0 & 1.10105 & 0 & -0.18577 \\ 1.10105 & 0 & 0.88528 & 0 \\ 0 & 0.88528 & 0 & 1.10105 \\ -0.18577 & 0 & 1.10105 & 0 \end{bmatrix}$$

In Fig. 4, simulation results for the steps in the previously described step-by-step procedure are shown. Five to seven single-frequency calculations at 15 GHz are used in each of the steps 1, 3, 5 and 7, to tune in the simulated $|S_{21}|$-values to the theoretical reference values for the structures in Fig. 3. Five to six simulations, each with 15 frequency points, are used in the calculations in steps 4, 6 and 8, to tune in the cavity lengths so that each cavity resonates at 15 GHz. The resulting physical dimensions are given in Fig. 5, along with a comparison between the simulated response of the complete filter and the ideal circuit response of the prototype filter. All irises are 1.0 mm thick, and the rectangular coupling hole between cavity 2 and cavity 3 is placed 2.45 mm from the end-wall of cavity 2.
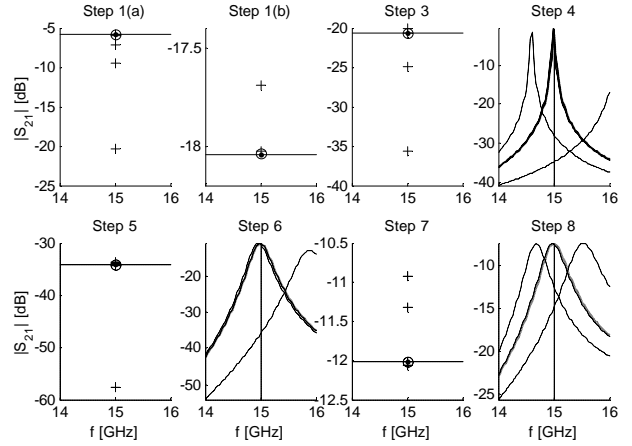
The filter has been produced at Nera using machining. In Fig. 6 measurements are compared to the theoretical response of the prototype filter. Good agreement is found between measurements, simulations and prototype filter response.

To indicate how the present method improves the often applied design process in which the intercoupling dependencies are ignored, the filter response after step 5 in the described design process is shown in Fig. 7. By comparing Fig. 5 and Fig. 7 it is evident that the present design procedure gives significantly improved results.

B. Six cavity cross-coupled filter

The mechanical dimensions of a six cavity filter with a cross coupling between the first and last cavity, center frequency of 18 GHz, and ripple bandwidth of 500 MHz, has been synthesized using the described procedure with a slight modification. The prototype filter has normalized input/output resistances $R_{in} = R_{out} = 1.1930$ and coupling matrix

$$M = \begin{bmatrix} 0 & 0.9498 & 0 & 0 & 0 & -0.0240 \\ 0.9498 & 0 & 0.6661 & 0 & 0 & 0 \\ 0 & 0.6661 & 0 & 0.6434 & 0 & 0 \\ 0 & 0 & 0.6434 & 0 & 0.6661 & 0 \\ 0 & 0 & 0 & 0.6661 & 0 & 0.9498 \\ -0.0240 & 0 & 0 & 0 & 0.9498 & 0 \end{bmatrix}$$

In Fig. 8 the simulated response of the designed filter is compared to the ideal circuit response of the prototype filter. From the figure it may be seen that there is good correspondence between the two cases. However, if the position of the two transmission zeros is critical, some fine-optimization is necessary.
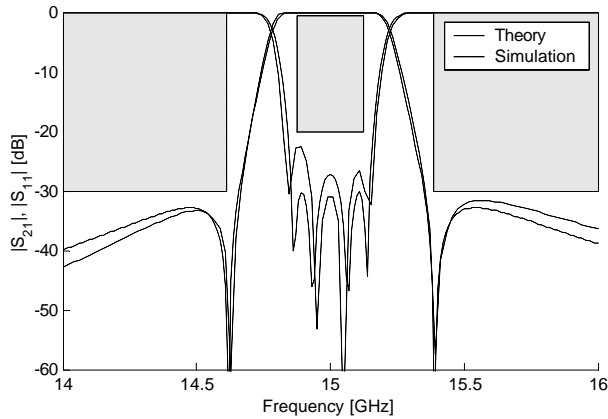
Fig. 5. Comparison between prototype filter response and simulated response of the four cavity cross-coupled filter. Filter dimensions are a=15.799 mm, b=7.899 mm, lr_1=11.174 mm, lr_2=12.329 mm, ai_{01}=7.071 mm, ai_{12}=4.192 mm, ai_{23}=6.781 mm, bi_{23}=3.0 mm and d_{14}=4.192 mm.
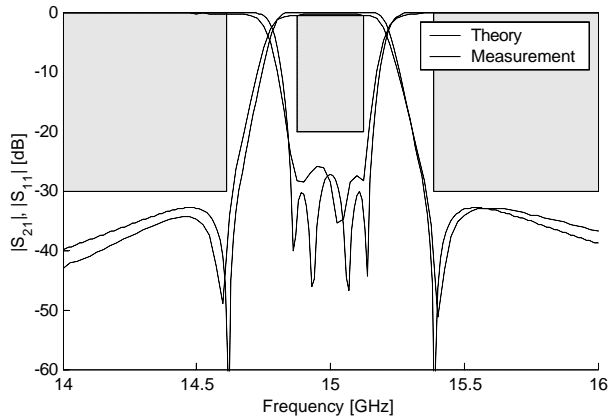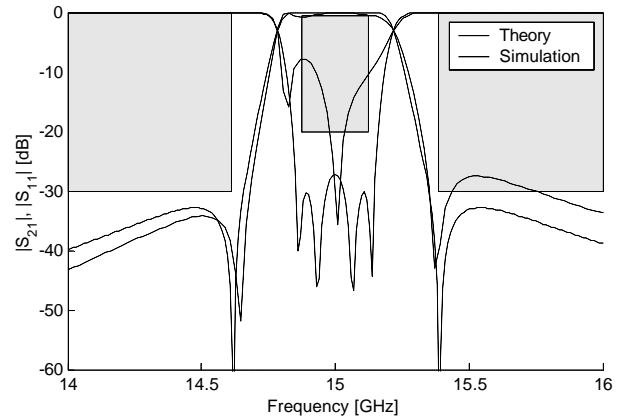
Fig. 7. The simulated response after step 5 in the described design process compared to the prototype filter response. In this case d_{14}=4.293 mm, lr_1=11.063 mm, and the other dimensions are as given in Fig. 5.
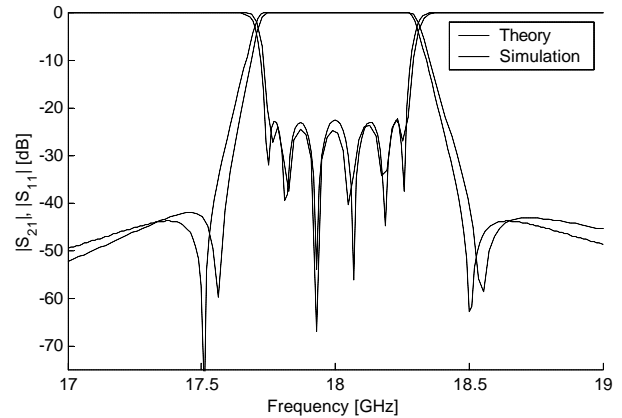
Fig. 6. Comparison between prototype filter response and measured response of the four cavity cross-coupled filter.

Fig. 8. Comparison between prototype filter response and simulated response of the six cavity cross-coupled filter.

IV. CONCLUSION

A general design procedure for folded waveguide filters with cross couplings has been presented. The usefulness of the method has been verified through simulations and measurements. The procedure has currently been applied to symmetric cross-coupled waveguide filters with one cross coupling, but can also be extended to filters with several cross couplings.

REFERENCES

[1] G. L. Matthaei, L. Young, and E. M. T. Jones, "Microwave filters, impedance-matching networks, and coupling structures," New York: McGraw-Hill, 1964 (Reprint Norwood: Artech House, 1980)

[2] M. Guglielmi, "Simple CAD procedure for microwave filters and multiplexers ," IEEE Trans. Microwave Theory Tech., vol. 42, pp. 1347-1352, July 1994

[3] S. Yin, T. Vasilyeva, and P. Pramanick, "Use of three-dimensional field simulators in the synthesis of waveguide round rod bandpass filters," Int. J. RF and Microwave Computer-Aided Engineering vol. 8, no. 6, pp 484-497, Nov 1998

[4] K. Folgerø, "Step-by-step procedure for design of waveguide filters with HFSS," Ansoft HFSS User Workshop, Los Angeles, January 2001

[5] T. Shen, K. A. Zaki, and A. E. Atia, "Full-wave design of canonical waveguide filters by optimization," 2001 IEEE MTT-S Int. Microwave Symp. Digest, vol. 3 pp. 1487-1490, June 2001

[6] J. R. Montejo-Garai, and J. Zapata, "Full-wave design and realization of multicoupled dual-mode circular waveguide filters," IEEE Trans Microwave Theory Tech vol. 43, no. 6, pp. 1290-1297, 1995

[7] A. E. Atia, and A. E. Williams, "A solution for narrow-band coupled cavities," COMSAT Technical Memorandum CL-39-70, 1970

[8] "Wasp-Net: Manual and design examples", Microwave Innovation group, Bremen, Germany, 2001