Fast and Accurate C.A.D. of Narrow Band Waveguide Filters Applying an Electromagnetic Segmentation Method

Delphine Bariant, Stéphane Bila, Dominique Baillargeat, Serge Verdeyme, Pierre Guillon

Ircom, 123 avenue Albert Thomas, 87060 Limoges, France

Abstract — **This paper outlines a segmentation method dedicated to filter design applying a Finite Element software. This method is particularly efficient, simple, accurate and fast to design dual-mode band-pass filters using simple models. Any numerical electromagnetic software can be used to realize the segmentation. At the end of the procedure, all the dimensions of the filter (cavities and irises) are known. The filter can be built without any modification of these dimensions during the tuning. The different stages of the procedure are described in this paper. The experimental results show good agreement with the theoretical ones.**

I. INTRODUCTION

Nowadays, advanced telecommunication systems involve an optimal use of allocated frequency bands. As a result, microwave engineers have to satisfy more and more severe electrical specifications to realize improved signal processing functions. A fast theoretical study becomes often necessary in order to predict the circuit behavior, intending to replace long and costly dummy realizations.

Microwave circuits may be studied applying appropriate synthesis methods to determine the electrical characteristics (couplings, input impedance, radiation resistance...) related to the desired function. Most of the synthesis methods are based on equivalent circuits composed of lumped elements which are directly related to these electrical characteristics. Applying the circuit theory, ideal electrical characteristics are determined in order to realize the desired function.

In our study, a simple method of dual-mode band-pass waveguide filters design is described. Generally, the design of a band-pass filter starts with the selection of an ideal transfer function which satisfies the filtering pattern. Classical synthesis methods [1]-[4] permits to determine the lumped element ideal values of the band-pass filter equivalent circuit presented in Fig.1.

All these values permit to define the coupling matrix of the filter which represents all the oscillation frequencies of the resonant elements in the structure and all the physical couplings which have to be realized between these resonant elements. All the terms of the coupling matrix are linked to physical dimensions of the filters.

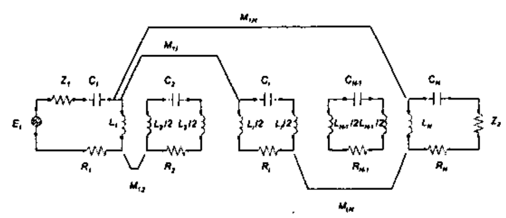

Fig.1. Narrow band band-pass filter equivalent circuit.

This paper outlines a segmentation method using a Finite Element software in order to established these links and to obtain the final dimensions of the filters. This method of segmentation is divided in several stages based on simplified structures to determine rapidly, with a good accuracy, the dimensions of the filters.

A 5-pole elliptic filter, described in Fig. 2., is designed to validate the segmentation method. The filter is built and tuned at the IRCOM without any modification of the dimensions (cavities and irises) that were obtained applying the segmentation method. The comparison between the theoretical results and the measurements validates the method.

II. PRESENTATION OF THE SEGMENTATION METHOD

The segmentation method is based on a numerical analysis performed applying free or forced oscillations two-dimensional (2D) or three-dimensional (3D) Finite Element Method between the access ports of the device. The software used is developed in our laboratory and it has already been explained in several papers [5]-[6], our purpose is not to described it here. However, the segmentation method can be realized easily applying any numerical electromagnetic software as HFSS.

The segmentation method is applied to the design of a 5-pole elliptic filter. The filter, presented in Fig.2, is excited on its TE_{113} dual-mode using two input/output irises. In each cavity, a screw at 45° angle from the polarization axes couples the dual modes and two tuning screws adjust the resonant frequencies to the central frequency. Single and cross irises ensure couplings between adjacent cavities. The structure is designed in order to obtain a filtering function characterized by a central frequency at

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12,350 GHz and a 37,5 MHz equiripple bandwidth. The required return loss is 23 dB in the pass-band and the insertion loss is 25dB out of the pass-band.

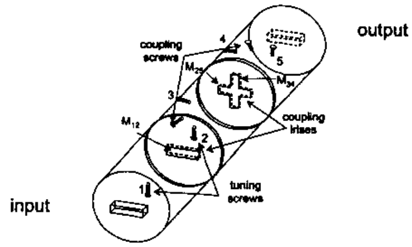

Fig.2. 5-poles elliptic dual mode filter.

Applying a classical synthesis method, the following normalized coupling matrix is determined:

$$Rin = 1{,}1299 \qquad Rout = 1{,}1299$$

$$[Mij] = \begin{bmatrix} 0 & 0{,}899 & 0 & 0 & 0 \\ 0{,}899 & 0 & 0{,}582 & 0 & -0{,}286 \\ 0 & 0{,}582 & 0 & 0{,}809 & 0 \\ 0 & 0 & 0{,}809 & 0 & 0{,}852 \\ 0 & -0{,}286 & 0 & 0{,}852 & 0 \end{bmatrix} \qquad (1)$$

All the matrix terms depend on the structure dimensions:

- The impedance values, R_{in} and R_{out}, are linked to the input and the output iris dimensions.
- The coupling coefficients M_{12}, M_{34} and M_{25} are fixed by the dimensions of the coupling irises (simple or cross one) between adjacent cavities.
- M_{23} and M_{45} characterize coupling screws.
- The terms M_{ii} show the frequency shift between the polarization i and the central frequency of the filter. These terms can be adjusted using tuning screws.

To compute the dimensions of the structure which satisfy the electrical requirements, the segmentation method is applied using simplified structures, corresponding to different segments of the filter, to decrease time and cost tuning. This method is divided in several stages:

A. Stage 1:Cavity dimensions.

The simplified structure used in this stage is presented in Fig.3.

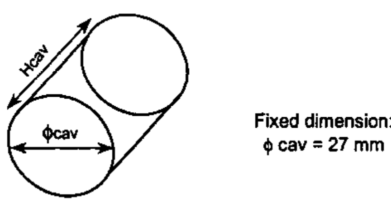

Fig.3. Stage 1 - Cavity dimensions.

The dimensions of the cavities have to respect center frequency of the filter. As it is well known, the resonance frequency of the cavity is naturally decreased by the presence of the coupling irises. As a consequence, we define the frequency f'_0 such as:

$$f'_0 = f_0 + 5\%\, f_0 \qquad (2)$$

First, we determine the dimensions of the intermediary cavity that is less influenced than the input or the output ones. Indeed, the intermediary cavity is coupled to the other cavities using irises that are less wide than the excitation ones. We determine the cavity height Hcav = 42,6mm in order to obtain a center frequency f'_0 = 12,413 GHz. The dimensions of the input and the output cavities will be determined during the stage 2, because of the influence of the excitation irises.

B. Stage2: Excitation irises dimensions - Adjustment of the height of the input and the output cavities.

Excitation irises have to respect the external factor Q_e determined using the following formula:

$$Qe = \frac{fo}{\Delta f * R} \qquad (3)$$

where f_0 is the center frequency, Δf the equiripple bandwidth and R, the input/output normalized impedances.

Q_e is computed applying the 3D forced oscillations using a simplified structure presented in Fig.4.

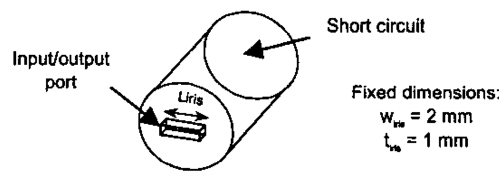

Fig.4. Stage 2 - Input/output iris dimensions.

Q_e is calculated on the phase of the reflection parameter S_{11}. The mode TE_{113} is excited through the iris connected to a standard waveguide that functioned on it fundamental mode. The iris and the standard waveguide introduce a phase shift that have to be annihilated to calculate the external factor. Fig. 5 presents the electromagnetic phase of the S_{11} of the structure presented on Fig. 4 and the same one with the shift phase compensated.

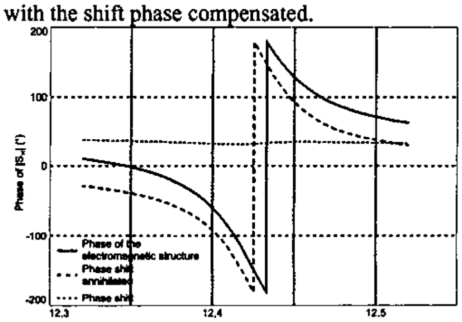

Fig.5. Stage 2 - Phase shift annihilated.

The external factor is calculated applying the following formula:

$$Q_e = \frac{f_0}{f(90°) - f(-90°)} \quad (4)$$

Fig. 6. presents the external factor Q_e as a function of the iris length L_{iris} for several cavity heights. The thickness t_{iris} and the width w_{iris} of the excitation iris are fixed.

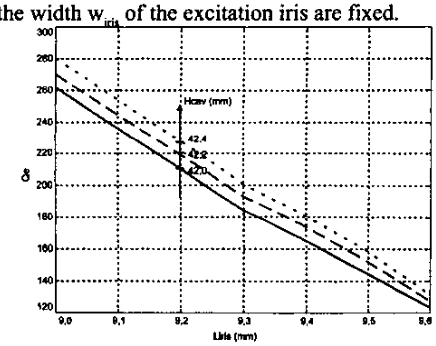

Fig.6. Stage 2 - Q_e factor for several lengths of irises

The length of the iris can be determined easily using this abacus (Fig.5.) and extrapolated for other heights of the cavities, considering the quasilinear variation of the Q_e factor for a selected interval of values. As an example, L_{iris}=9,54mm for H_{cav}=42,2mm to obtain desired Q_e=291,5.

To adjust the heights of the input and output cavities, the structure presented on Fig. 7 is considered.

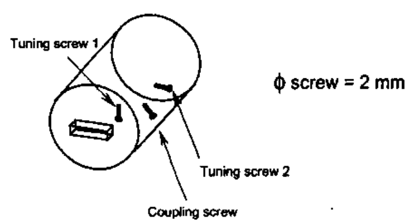

Fig.7. Stage 2 - Adjustment of the dimensions.

As it is shown in Fig.2., the input cavity presents one tuning screw (n°1) to adjust the excited polarization through the coupling iris at the central frequency f_0. The 3D free oscillation is applied to this structure for different lengths of tuning screw and the height of the cavity is determined to respect the guard band ($f'_0 = f_0 + 5\% f_0$) and to obtain correct physical dimensions of the tuning screw: not too short to preserve a tuning effect, not too long to decrease the influence on microwave breakdown ignition [7]. The output cavity presents a screw at 45° angle from the polarization axes which couples the dual modes and two tuning screws that adjust the resonant frequencies. The height of the cavity is adjusted, as it is explained previously.

Then, the excitation iris lengths are adjusted to the desired external factor using the 3D forced oscillations. Indeed, considering the structure presented in Fig. 7 and the iris length obtained earlier L_{iris}=9,54mm (without the screws), the external factor obtained is Q_e=234 that is far from the objective. The iris length must be adjusted to realize the desired factor Q_e. The presence of the screws disturbs the external factor and we realize the adjustment of the iris length to obtain L_{iris}=9,30mm for H_{cav}=42,2mm.

C. Stage3: Coupling irises between adjacent cavities.

The desired coupling values K_{ij} are determined with the coupling matrix terms M_{ij} using the following formula:

$$K_{ij} = \frac{M_{ij} * \Delta f}{f_0} \quad (5)$$

The simplified structure presented on Fig. 8 is analyzed applying the 3D free oscillation. The coupling coefficient K_{ij} are determined for several heights of cavities, applying:

$$K_{ij} = \frac{f_1^2 - f_2^2}{f_1^2 + f_2^2} \quad (6)$$

where f_1 and f_2 are the resonant frequencies of the dual mode.

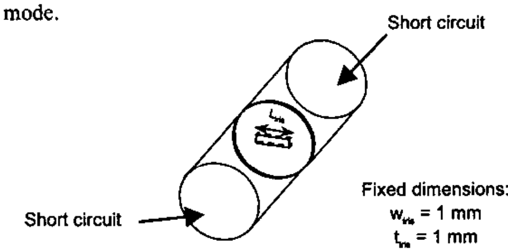

Fig.8. Stage 3 - Coupling iris dimensions

The coupling coefficient K_{ij} between the two polarizations is computed for different lengths of the iris and different heights of cavities. The thickness t_{iris} and a width w_{iris} of the coupling iris are fixed.

Fig. 9. presents the coupling coefficient as a function of the iris length L_{iris}. Using this abacus we determine the lengths of coupling irises between the adjacent cavities:

- for M_{12}, L_{iris} = 7,40 mm,
- for M_{34}, L_{iris} = 7,76 mm
- for M_{25}, L_{iris} = 6,1 mm

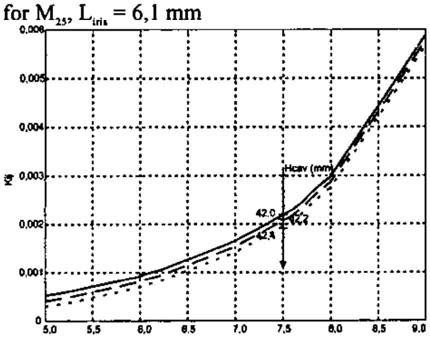

Fig.9. Stage 3 - Coupling between the two polarizations

Although the length of the simple iris can be determined with this abacus to satisfy the M_{12} coupling value, the lengths of the cross iris have to be adjusted to take into account the interaction between the two arms of the iris. This adjustment is realized applying the 3D free oscillation to the structure presented in Fig. 10.

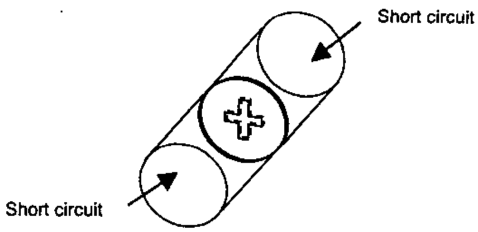

Fig. 10. Stage 3 - Adjustment of the cross coupling iris dimensions

Consequently, the lengths of the cross coupling iris are:

- for M_{34}, L_{iris} = 7,15 mm
- for M_{25}, L_{iris} = 5,47 mm

D. Stage: Experimental measurements.

The final dimensions of the different elements of the filter are:

- Input cavity: ϕ = 27,00 mm, H = 42,20 mm
  Intermediary cavity: ϕ = 27,00 mm, H = 42,60 mm
  Output cavity: ϕ = 27,00 mm, H = 42,20 mm
- Input excitation iris: (9,30 * 2,00 * 1,00) mm
  Simple iris: (7,40 * 1,00 * 1,00)mm
  Cross iris: (7,14 * 5,47 * 1,00 * 1,00)mm
  Output excitation iris: (9,30 * 2,00 * 1,00)mm

The filter has been built, tuned and tested at the IRCOM, machining only the cavities and only the irises determined by the segmentation method. The different elements of the filter are machined with a mechanical precision of ± 0,02 mm. Fig. 11 shows the experimental results compared to the theoretical ones established using an equivalent circuit.

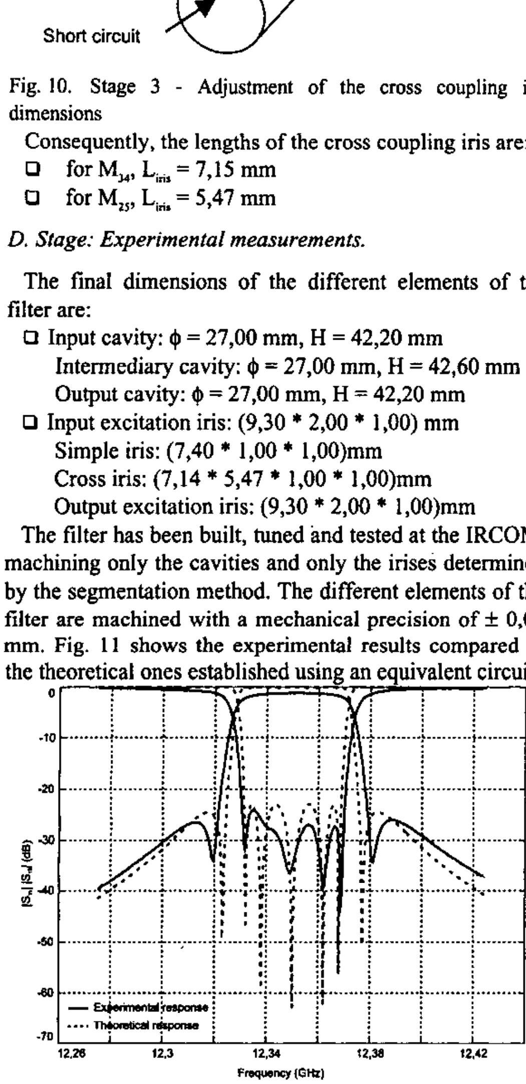

Fig. 11. Experimental results.

The comparison between the theoretical results and the measurements permits to validate the accuracy of the method of segmentation described in this paper. Indeed, the experimental central frequency is f_0=12,350GHz and the equiripple bandwidth is 38MHz. The metallic losses are about 1,15 dB because the cavities, all the irises and the screws are machines in brass (σ = 7,69*10^4 S.m^{-1}). Although the machining precision obtained at the IRCOM is far from industrial one, the experimental results are in agreement with the theoretical ones. Then, we can consider that the segmentation method can be realize with a precision of the dimensions near the machining one. Consequently, the different stages of the method can be realize without using structures so meshing (λ_{used}/5 for cavities and λ_{used}/60 for irises) that is permit to reduce the time cost.

III. Conclusions

This paper focuses on a fast, accurate and simple synthesis method developed to design microwave filters and using a finite element software. This method of segmentation provides rigorously all the dimensions of the filter in order to realize the desired transfer function. The segmentation is based on simplified structures that can be designed using a classical numerical software. We have demonstrated the efficiency of this method applying it to design a 5-poles elliptic dual-mode filter. As we can observe, a good agreement is satisfied between theoretical and experimental results obtained with only one set of irises and cavities determined with this method.

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