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Systematic procedure for the efficient design of folded waveguide comb-line filters

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***Abstract*—A systematic procedure for the efficient design of folded waveguide comb-line filters is presented. The proposed strategy is based on dividing the design process in more simple stages, in order to reduce the number of variables to be optimized in each step of the design process. The electrical response of an equivalent circuit model of the waveguide component considered in each step is used as a target response. Moreover, a method for obtaining an initial value for some key dimensions of the filter is also addressed. Finally, an S-band 6-pole folded comb-line filter has been successfully designed following the proposed design strategy.**

***Index Terms*—Folded comb-line filters, design process.**

I. INTRODUCTION

The objective of this work is to describe a systematic procedure for the design of waveguide comb-line filters implemented in folded configuration. The design strategy is based on an equivalent circuit model of the filter composed of ideal impedance inverters and lumped elements [1]. Concretely, each resonator will be modelled in terms of a series L-C resonant circuit, thus achieving a simpler representation of the cavity resonance by means of lumped elements. In addition, with the aim of reducing the number of variables to be optimized during the process, we propose to divide the problem into simpler stages, so that the different resonators of the filter are progressively added one after the other [2]. The electrical response of the ideal network related to the waveguide component considered in each stage will be used as a target response in each step of the design process. Besides, we will also discuss the strategy used to obtain the initial values for some of the key dimensions of the filter, thus ensuring the rapid convergence of the optimization process. This novel design strategy will be used in the practical design of a sixth-order Chebyshev band-pass filter (see Fig. 1), with 20 dB of return loss, centred at $f_0 = 3.62$ GHz, and considering a bandwidth of 20 MHz.

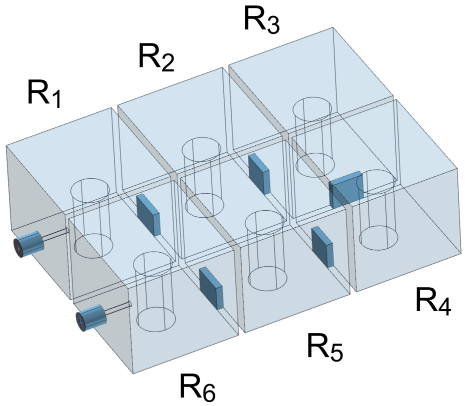

Fig. 1. Folded comb-line filter composed of 6 resonators.

II. DESIGN OF THE COMB-LINE RESONATOR

The comb-line resonator consists of a rectangular cavity loaded with a cylindrical metallic post placed at a centred position (see Fig. 1). The dimensions of the structure must be designed so that the first mode of the component resonates at f_0. The process usually starts by choosing a cylindrical post whose length is smaller than a quarter wavelength at f_0 (the cited length provides us with a set of initial dimensions for the rectangular enclosure) [3]. Afterwards, all the dimensions need to be further optimized to adjust the resonance of the cavity to the desired value (the software tool FEST3D, v. 2018 from AuroraSAT, now with CST, has been used in the whole design process). The final dimensions of the rectangular enclosure (width, height and length) are: 27.0 mm × 23.1 mm × 25.0 mm; while the height and radius of the loading post are 15.33 mm and 4.1 mm, respectively.

III. EQUIVALENT CIRCUIT MODEL OF THE FILTER

The objective of this section is to obtain an ideal network of the filter in terms of ideal impedance inverters and lumped elements. To this aim, each resonator of the waveguide filter will be characterized in terms of a series L-C resonant circuit. The values L and C of the lumped elements can be readily calculated, after computing the slope parameter of the comb-line resonator designed in the previous section by means of full-wave simulations [4]:

$$X = \frac{w_0}{2} \left. \frac{dX_{in}(w)}{dw} \right|_{w=w_0} = Lw_0, \tag{1}$$

where X represents the slope parameter of the resonator, $w_0 = 2\pi f_0$, and X_{in} is the reactance of the input impedance of the cavity (the capacitance C can be obtained as $C = 1/(w_0^2 L)$). In this case, the values of the lumped elements are $L = 2.656$ nH and $C = 0.727$ pF. In order to confirm the validity of this procedure, we first calculate the reactance of the derived L-C series resonant circuit and, next, we proceed to compare it with the reactance of the waveguide resonator computed using full-wave simulations. The results obtained are shown in Fig. 2, where an excellent agreement between both curves is found around the resonant frequency f_0. The ideal network of the filter is displayed in Fig. 3, where only one half of the circuit is represented, since the filter is symmetrical.

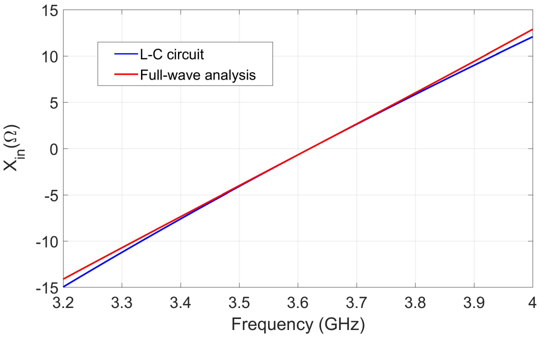

Fig. 2. Reactance of the resonator. The reactance computed starting from electromagnetic calculations (red curve) is compared to the circuital reactance (blue curve).

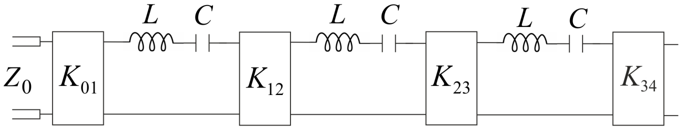

Fig. 3. Equivalent circuit model of the filter (only one half of the ideal network is shown).

IV. Initial dimensions for the coaxial lines

First of all, we are interested in obtaining an initial value for some key dimensions concerning the coaxial waveguides used in the input and output ports: the distance (from the bottom of the filter) at which the coaxial feeding lines should be placed, and the depth of penetration of the coaxial probes (note that, in this design, the probes are not in contact with the loading posts of the input and output resonators). To this end, we propose to analyse the resonator designed in section II, only fed by a coaxial waveguide ($r_{out} = 2.1$ mm, $r_{in} = 0.635$ mm, $\epsilon_r = 2.1$). Next, we obtain the ideal network related to this waveguide component (it can be readily derived starting from the circuit shown in Fig. 3, after short-circuiting the input port of the inverter K_{12}), and compute its electrical response in terms of the group delay of the S_{11} parameter. Finally, the dimensions of the waveguide structure are optimized considering the electrical response of the ideal network as a target curve. After this optimization (we only optimize 3 variables), we obtain the following dimensions: offset of the coaxial ports of 6.721 mm, depth of penetration of the coaxial probes of 6.899 mm, and height of the post of 15.137 mm. Fig. 4 shows the result of the optimization, where an excellent agreement between the full-wave response and the reference curve is observed.

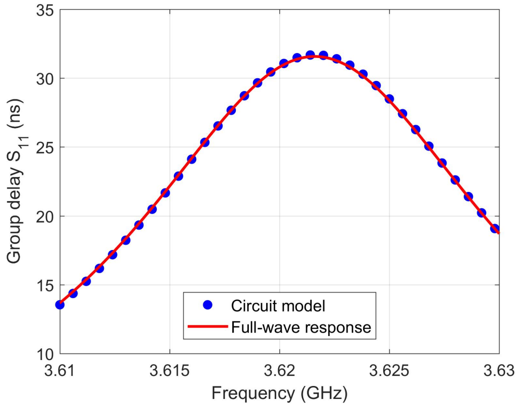

Fig. 4. Results of the optimization performed for obtaining an initial value for the offset and depth of penetration of the coaxial lines.

V. Initial dimensions for the rectangular windows

The resonators of the comb-line filter are coupled by means of rectangular windows. This section aims at describing a systematic procedure for obtaining a set of initial dimensions (width and height) for these coupling windows (the thickness of the windows is set at 1.5 mm). First of all, we will address the characterization of the iris connecting resonators R3 and R4 (see Fig. 1).

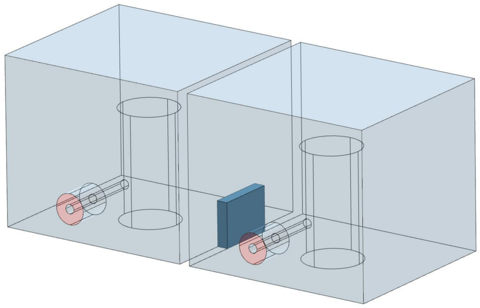

Fig. 5. Waveguide component considered for the obtention of the initial dimensions of the iris connecting resonators R3 and R4.

To this end, we consider the symmetrical structure in Fig. 5, where two comb-line resonators, excited using coaxial lines, have been coupled through a rectangular iris. The corresponding ideal network is composed of the cascaded connection of the input transmission line, inverter K_{01}, L-C series resonant circuit, inverter K_{34}, L-C series resonant circuit, inverter K_{01}, and output transmission line. The electrical response (S_{21} parameter) of this ideal network will be used as a target response. The results of the optimization, which are shown in Fig. 6, provides us with an initial dimension for the height of the iris equal to 6.232 mm.

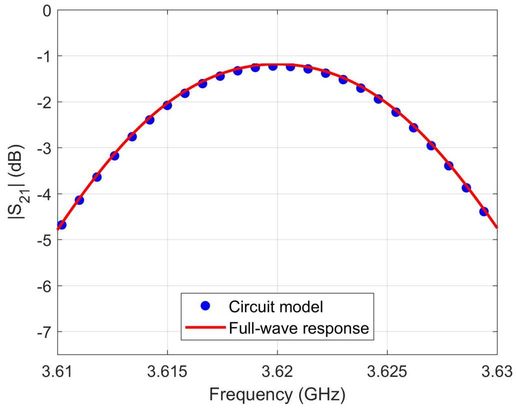

Fig. 6. Results of the optimization performed to determine an initial dimension for the height of the iris connecting resonators R3 and R4.

In order to obtain an initial value for the width of the iris, the electromagnetic coupling of the waveguide component considered in Fig. 5 is computed in terms of the width of the window. As we are interested in obtaining the resonant frequencies of the structure, note that a very weak coupling is required on both input and output ports. According to the ideal network, the electromagnetic coupling between resonators R3 and R4 is 0.00322. Therefore, the required width of the iris is found to be equal to 7.250 mm.

The same procedure can be employed for obtaining a set of initial dimensions for the coupling windows connecting resonators R1 and R2, and R2 and R3. This time, the symmetrical structure in Fig. 7 should be considered. After performing the corresponding optimization process, the initial dimension for the height of the windows is found to be equal to 6.264 mm. With this approach, a parametric curve of the electromagnetic coupling in terms of the width of the windows can be readily obtained. In this case, the required widths of the windows are 7.510 mm (iris connecting R1 and R2) and 6.650 mm (iris connecting R2 and R3).

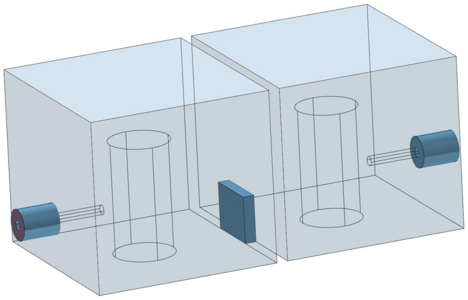

Fig. 7. Waveguide component considered for the obtention of the initial dimensions of the windows connecting resonators R1 and R2, as well as R2 and R3.

VI. DESIGN OF THE FILTER USING A STEP-BY-STEP STRATEGY

The design process is divided into simpler stages, so that the different resonators of the filter are progressively added. The electrical response (group delay of the S_{11} parameter) of the ideal network related to the waveguide component considered in each step will be taken as the target response. The objective is to optimize the dimensions of the waveguide structure in order to match its full-wave response with the one of the ideal network. Besides, the optimized dimensions obtained in each step will be used as the starting point for the next step.

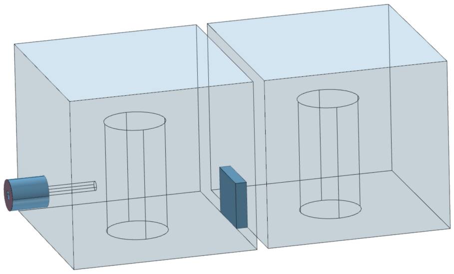

Fig. 8. Waveguide component considered in the first stage of the design process.

In the first stage, two resonators are considered (see Fig. 8). The component has only one access port implemented in coaxial waveguide. In this first step, the initial dimensions obtained in the previous sections are used as a starting point in the optimization process.

The equivalent circuit of this waveguide component consists of the cascaded connection of the input transmission line, inverter K_{01}, L-C series resonant circuit, inverter K_{12}, and another L-C series resonant circuit short-circuited at its end. In this first step, the dimensions to be optimized are the height of the loading posts, the width and height of the iris, and the offset and depth of penetration related to the input coaxial port. The results of the optimization can be found in Fig. 9, where a very good agreement is observed between the electrical responses of the waveguide component and its corresponding ideal network.

In the next stages, the different resonators are progressively added. For the sake of brevity, we will omit the results of the second step, and we directly show next the results of the third stage, where four resonators are considered. The waveguide structure is shown in Fig. 10 (the equivalent circuit model of this component can be easily deduced starting from the ideal network used in the first stage). In this step, the dimensions to

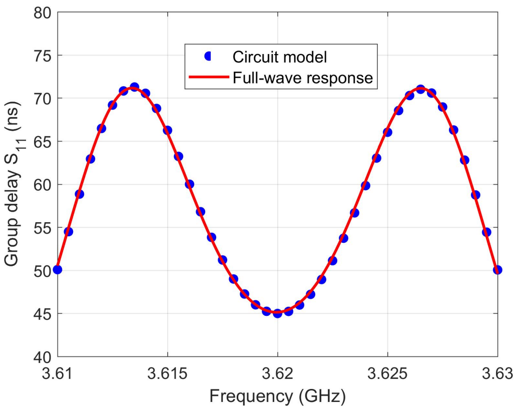

Fig. 9. Electrical response of the structure of Fig. 8 compared to the ideal response.

be optimized are the height of the loading posts, the width and height of the windows, and the offset and depth of penetration related to the coaxial line.

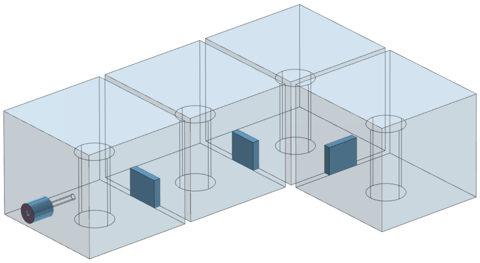

Fig. 10. Waveguide component considered in the third stage of the design process.

The results of the optimization are displayed in Fig. 11, where a very good agreement is again observed between the circuit model response and the full-wave response.

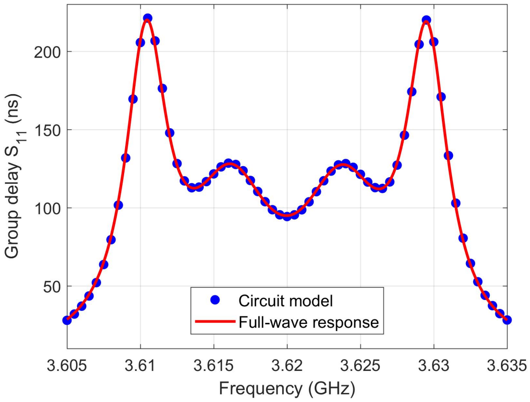

Fig. 11. Electrical response of the structure of Fig. 10 compared to the ideal response.

Once we have designed one half of the component (note that the filter is symmetrical), we can address the optimization of the whole filter (see Fig. 1). In this last stage, the S_{11} parameter of the ideal network is considered as the target response. The results of the optimization can be found in Fig. 12, where the response obtained using the commercial tool HFSS (v. 19.1.0 from ANSYS) is shown. A very good agreement is observed between the full-wave data and the response of the ideal network, thus validating the systematic procedure proposed in this work. On the other hand, the final dimensions of the filter are reported in Table I.

TABLE I
DIMENSIONS (IN MM) OF THE FOLDED COMB-LINE FILTER.

Height of the posts of resonators R1, R2 and R3	15.065/15.221/15.242
Width of the iris R1-R2, R2-R3 and R3-R4	7.559/6.604/7.269
Height of the iris R1-R2, R2-R3 and R3-R4	5.797/6.106/6.305
Thickness of the iris R1-R2, R2-R3 and R3-R4	1.5
Offset and depth of penetration of the coaxial lines	6.689/6.711

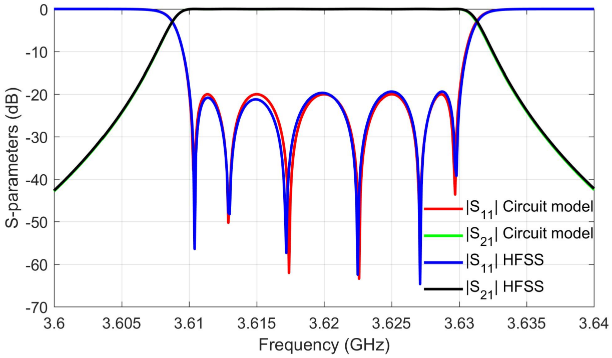

Fig. 12. S-parameters of the folded comb-line filter depicted in Fig. 1.

VII. CONCLUSION

In this work, a systematic procedure for the efficient design of folded comb-line filters has been presented. The proposed strategy is based on dividing the design process into simpler stages, with the aim of reducing the number of variables to be optimized in each step. Besides, the electrical response of an equivalent circuit model of the waveguide component, based on lumped elements, has been used as a target response during the design process. The proposed approach has been successfully validated through the practical design of a 6-pole band-pass filter operating in the S-band.

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