

# Compact Wideband Stepped Impedance Filters with Resonant Apertures

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**Abstract**— This article describes a novel compact wideband filter topology in rectangular waveguide technology, and the related design procedure. The filter structure is based on the combined use of stepped impedance resonators (SIRs) and resonant apertures (RAs). The RAs increase the selectivity without enlarging the structure of the filter. The novel design procedure that we introduce results into a substantial improvement of the out-of-band response as well as a very compact structure. As an example, a nine-pole prototype is designed, fabricated and measured showing an excellent agreement with the predicted response.

**Keywords**— Filter design, resonant apertures, stepped impedance resonator, waveguide filters, wideband filters.

## I. INTRODUCTION

Current wireless communication equipment, for both ground and space applications, require ever smaller and more compact components. In this context, therefore, researchers are devoting very significant efforts to the study of new structures that have considerably reduced size while exhibiting improved performance. Within the scope of microwave filters in particular, wideband filters, have historically been problematic both in terms of design and performance due to the appearance of replicas and spurious responses close to the pass-band.

The structures extensively studied for narrowband applications, such as direct-coupled cavities through inductive or capacitive irises [1], degrade their performance significantly when used for wideband filter designs. Recently, in order to improve the out-of-band behavior of inductive filters in rectangular waveguide, stepped impedance resonators (SIRs) have been proposed as an alternative solution [2]. This technique has proved to be very effective against one of the limitations of conventional inductive filters, namely, the presence of spurious responses near the pass-band [3].

In addition, another possibility to design rectangular waveguide filters is to use resonant apertures (RAs), obtaining very selective filters, as discussed in [4], [5] and [6], where RAs behave as resonators and as mixed (inductive and capacitive) couplings simultaneously. This feature allows to increase the filter order while keeping the overall size rather small. Recently, staircase configurations with transmission zeros (TZs) have been studied for improving the out-of-band performance of filters based on RAs with excellent results [7]. In this last contribution, a very compact WR90 filter is obtained, where the spurious-free band is increased by using stubs in combination with a staircase configuration. However, the response of the filter is degraded after 12 GHz.

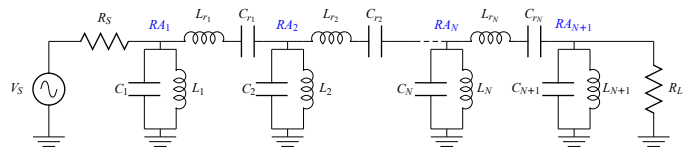


Fig. 1. Pass-band lumped element model.

In this context, therefore, this paper is focused on the design of a new family of compact wideband waveguide filters with a significant improvement of the out-of-band response. The novel structure is based on the combined use of SIRs and RAs. In particular, the dual function of the RAs will allow us to increase the order of the filter, thus obtaining better selectivity, without compromising the total filter size. Moreover, the layout is simpler than previous designs, thus requiring less demanding fabrication processes. The synthesis procedure and design methodology are described in section II. In section III, as a validation example, a tuningless prototype is designed, manufactured and measured obtaining an excellent agreement with the simulated response. The paper is concluded with a summary of the results obtained in section IV.

## II. DESIGN PROCEDURE

The synthesis of a wideband waveguide filter composed of SIRs and RAs is summarized next as a list of simple steps. The ultimate goal is to achieve a waveguide model that can be built, starting from the most basic (lumped lowpass) prototype, and going through the different models up to the final structure. Since the filter is wideband, we design the filter in waveguide technology to have a higher power handling capacity. Starting from a classical in-line ladder network, the proposed procedure is as follows:

- 1) We first obtain the values of the lumped lowpass prototype, the  $g_i$  values, of the Chebyshev filter with return loss  $RL$  and order  $N$  (odd). The filter shall be of order  $N = N_a + N_c$ , where  $N_a = (N + 1)/2$  will be the number of RAs, and  $N_c = (N - 1)/2$  will be the number of resonant cavities.
- 2) The second step is to choose an impedance  $Z_0$  for the denormalization process, and perform the low-pass to band-pass transformation (see Fig. 1). Parallel resonators (future RAs) are located between adjacent series resonators (future half-wavelength cavities).
- 3) Next, in order to replace the series resonators by real elements, i.e. by lengths of rectangular waveguide,

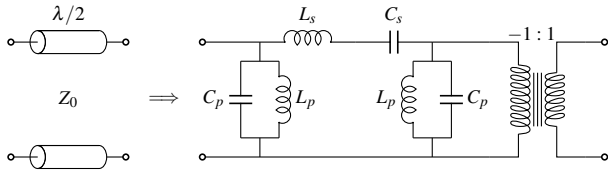


Fig. 2. Half-wavelength resonator modeled as a  $\pi$ -network near the resonance.

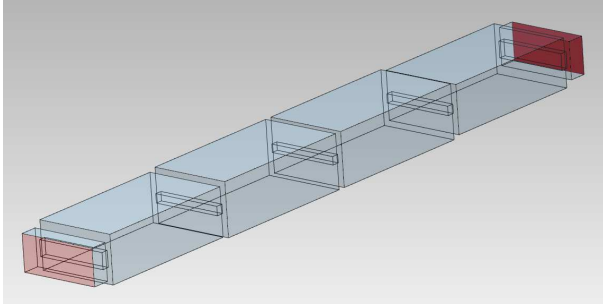


Fig. 3. Waveguide filter with RAs ( $N_a = 5$ ) and half-wavelength resonators ( $N_c = 4$ ).

it is necessary to calculate the values of certain parameters, such as the waveguide wavelength  $\lambda_{gi}$ , the slope parameter  $\chi_i$  and the characteristic impedance  $Z_{0i}$  of every  $i$ -th series resonator. These parameters allow us to obtain the dimensions  $a_i$  (waveguide width) and  $b_i$  (waveguide height) for each rectangular cavity (resonator). We now recall that half-wavelength waveguide resonators can be represented near the resonance by a  $\pi$ -network formed by two shunt resonators and a series resonator, as detailed in Fig. 2. At this point, the process that we have used to adjust the values of the shunt resonators, due to the influence of parasitic capacitance and inductance introduced by the half-wavelength waveguidewaveguides (used to replace the series resonators), is the one discussed in [7].

- 4) Next, the shunt resonators of the lumped elements model can be replaced by RAs. The whole procedure can be carried out just matching the response of every shunt resonator with the corresponding iris with suitable dimensions. After assembling all RAs with half-wavelength resonators, a simple optimization produces the waveguide bandpass filter shown in Fig. 3, with the electrical response shown in Fig. 4. We can appreciate the proximity of the first replica and the spurious responses in the whole WR-90 frequency band. It is interesting to note that the replicas are only due to harmonics of the half-wavelength resonators ( $N_c = 4$  in this case), since the RAs behave as lumped element resonators (in the frequency range of interest) and do not produce any replicas.
- 5) One point that is important to note is that in order to increase the power handling capability of the filter, the dimensions  $b_i$  of the RAs must be increased. This is achieved through shifting the irises to the bottom of the waveguide (see Fig.5). Therefore, the new values of  $a_i$

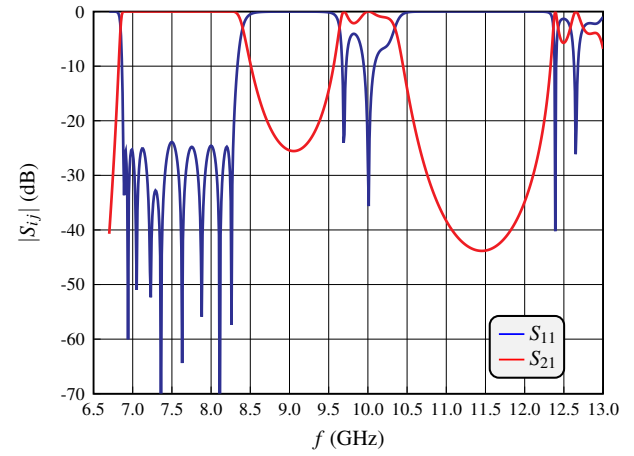


Fig. 4. Response of a 9-th order filter with RAs and half-wavelength waveguide resonators.

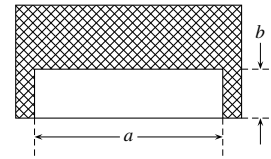


Fig. 5. Front view of an RA with dimensions  $a$  (width) and  $b$  (height) located at the bottom of the waveguide structure.

and  $b_i$ , that give an identical response to the original (centered) iris, need to be found. This change will help further optimizations and reduce the risk of  $b_i$  taking impractically small values.

- 6) The next step is to use SIRs to significantly improve the out-of-band response of the filter obtained in Fig. 4. To this end, each cavity in Fig. 3 is divided into three sections with a length value of  $1/3$  of the original half-wavelength cavity. The responses of the uniform isolated cavities are used as reference functions for the optimization of the dimensions of the SIRs (see for instance Fig. 6). Each SIR has 6 variables (2 per section) to be optimized: three lengths and three heights, in total. The middle section of the SIR must have a shorter height [3]. At this point, it is necessary to optimize each cavity. When the structure composed of a SIR between two RAs is created, the dimensions of each section and the adjacent irises are optimized to recover the response of the original isolated cavity. The main objectives of the optimization are to maintain correct in-band response and reduce the level of the out-of-band  $S_{21}$  parameter (Fig. 7).
- 7) Once each SIR is optimized, the complete filter can be assembled. At this point, an additional fine optimization is required to obtain the final response. After that optimization, the in-band response will be basically identical to the one obtained without SIRs (step 4), satisfying the specifications within the pass-band. However, the out-of-band response will be noticeably enhanced.

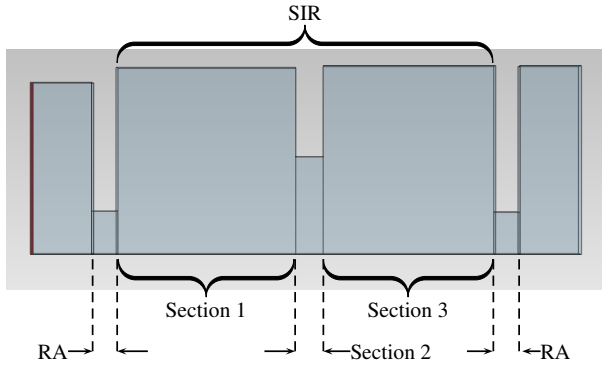


Fig. 6. Lateral view of a SIR, between 2 RAs, divided into 3 sections.

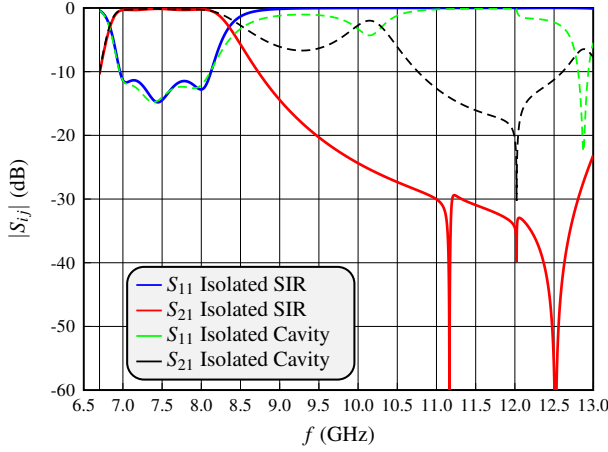


Fig. 7. Electrical response of an isolated SIR (and the two adjacent RAs) compared with the same structure using a uniform resonator.

### III. DESIGN EXAMPLE

To validate the procedure described in section II, we now apply it to the design of a breadboard of a wideband WR90 filter based on RAs and SIRs. The electrical specifications are shown in Table 1. Fig. 8 shows the structure of the filter. Since our final aim is to fabricate a tuning-less filter in clam-shell configuration, in the final structure we have replaced all sharp corners with rounded corners with a radius  $r = 1.1$  mm. The final optimization was then performed using the Agressive Space Mapping (ASM) technique [8], where FEST3D has been used as the Low Accuracy (LA) space, and HFSS as the High Accuracy (HA) space.

Table 2 contains the final values for the dimensions of our breadboard, where the filter is symmetrical about its center (iris 3), and the thickness ( $t_i$ ) of each RA is 2 mm.

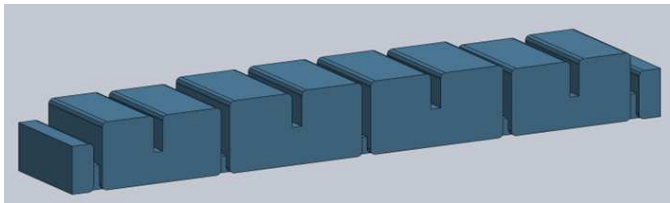


Fig. 8. Structure of the wideband waveguide filter with SIRs and RAs.

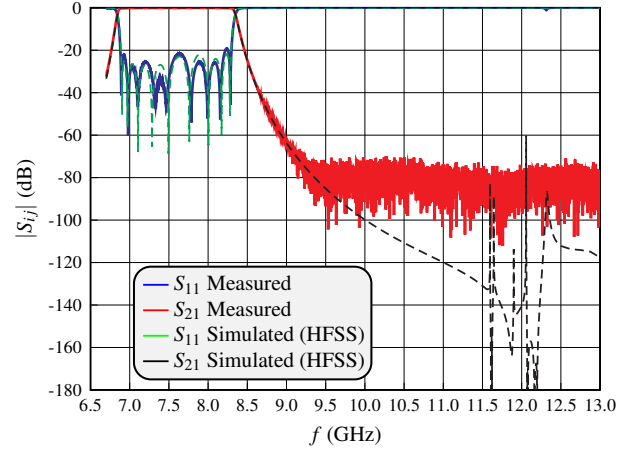


Fig. 9. Measurement of the performance of the filter compared with the EM simulation in HFSS.



Fig. 10. Manufactured prototype in aluminum.

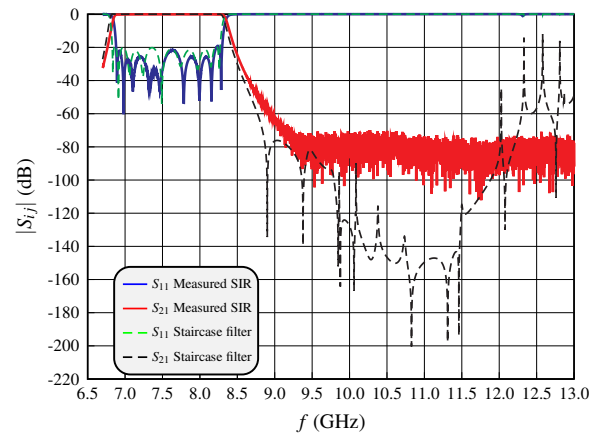


Fig. 11. Measurement of the performance of the filter compared with a staircase design [7].

Table 1. Electrical specifications for our design example.

Parameter	Goal
Order	9
Bandwidth	$BW = 1.4$ GHz
Return loss	$RL > 22$ dB
Center frequency	$f_0 = 7.55$ GHz
Fractional bandwidth	$\mathcal{W}_\lambda = 106.6$ %
WR-90 Waveguide	$a = 22.86$ mm $b = 10.16$ mm

Table 2. Physical dimensions for the wideband waveguide filter with SIRs and RAs. (S. means Section).

Section Type	Dimensions (mm)
Input/Output Waveguide	$a = 22.86$ $b = 10.16$ $L_{input} = L_{output} = 5$
Resonant Aperture 1	$a_1 = 20.394$ $b_1 = 5.203$ $t_1 = 2$
Resonant Aperture 3	$a_3 = 19.854$ $b_3 = 3.471$ $t_3 = 2$
Resonant Aperture 5	$a_5 = 19.661$ $b_5 = 3.508$ $t_5 = 2$
Resonator 1	S. 1 $a = 22.86$ $b = 14.348$ $L = 12.009$ S. 2 $a = 22.86$ $b = 6.600$ $L = 2.060$ S. 3 $a = 22.86$ $b = 14.163$ $L = 13.631$
Resonator 2	S. 1 $a = 22.86$ $b = 15.234$ $L = 14.517$ S. 2 $a = 22.86$ $b = 7.968$ $L = 2.309$ S. 3 $a = 22.86$ $b = 15.471$ $L = 14.023$

Fig. 9 shows the comparison between the results for the simulated structure (see Fig. 8) and the measurements of the real filter in Fig. 10. The in-band response agrees very well with the simulations, and the nine reflection zeros are clearly visible. However, the in-band return loss does show a minimal degradation near the band edges. The measured insertion loss is lower than 0.14 dB. Furthermore, the filter exhibits an extremely wide spurious-free range that goes up to the upper limit of the X-band. This improvement is very noticeable if we look at Fig 11, which compares the measured response with results of the new prototype with those of the staircase filters with stubs proposed in [7], that fulfils the same in-band specifications. It is worth noting the simplicity of the structure proposed in this paper, and its better out-of-band behaviour compared to the staircase filter.

#### IV. CONCLUSION

In this paper, we have shown that the combination of SIRs and RAs can effectively be used to develop a new family of compact wideband filters in rectangular waveguide, that is ideal for applications where the out-of-band performance

must be free of spurious responses in a wide frequency range. The combination of SIR and RA has proved to be an interesting innovation for future related works. In addition, the structure that we propose is indeed easy to manufacture, and the footprint of the filter is very small, making it an ideal solution for modern wireless payloads, for both ground and space applications, where improved performance and size reduction are driving requirements.

#### ACKNOWLEDGMENT

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