Novel Design of H-plane Bandpass Waveguide Filters Using Complementary Split Ring Resonators

S. Stefanovski[1], **D. Mirković**[1,2], **M. Potrebić**[1], **and D. Tošić**[1]

[1]School of Electrical Engineering, University of Belgrade
P. O. Box 35-54, Belgrade 11120, Serbia
[2]National Severe Storm Laboratory (NOAA), CIMMS, University of Oklahoma
120 David L. Boren Blvd, Norman, OK 73072, USA

Abstract— In this paper, a novel design of bandpass waveguide filters, using complementary split ring resonators is proposed. Resonators are implemented as inserts in a form of metal plates, with properly shaped slots, in the transverse planes of the rectangular waveguide. Filter response has been investigated for various parameters of the resonator and its position. Simple design of dual-band filter is introduced, using resonators attached to the top and bottom waveguide wall. Also, second-order dual-band filter is proposed.

1. INTRODUCTION

In communication systems where high-power structures with small losses need to be implemented, waveguide filters are of particular interest. These filters are usually implemented by inserting discontinuities of various shapes and positions in the waveguide. These discontinuities operate as resonators, thus by setting their parameters and positions, central frequency and bandwidth of the filter can be controlled. For bandpass waveguide filter design, complementary split ring resonators (CSRR) have wide implementation, either as single-mode or multi-mode. In previous publications, various design methods for filters with a single frequency band, using CSRRs, are proposed: implementation in the microstrip technology with defected ground structure as in [1, 2], using substrate integrated waveguide [3] or using rectangular waveguide [4–6]. Multi-band filter design is particularly attractive these days, so this topic calls for closer attention. Therefore, dual-mode resonators can be applied by properly combining single-mode resonators and dual-band filters are developed in this manner. One of the main characteristics of dual-mode resonators used for the filter design is that the resonators can be independently tuned [7], hence each frequency band can be independently controlled, as presented in [8].

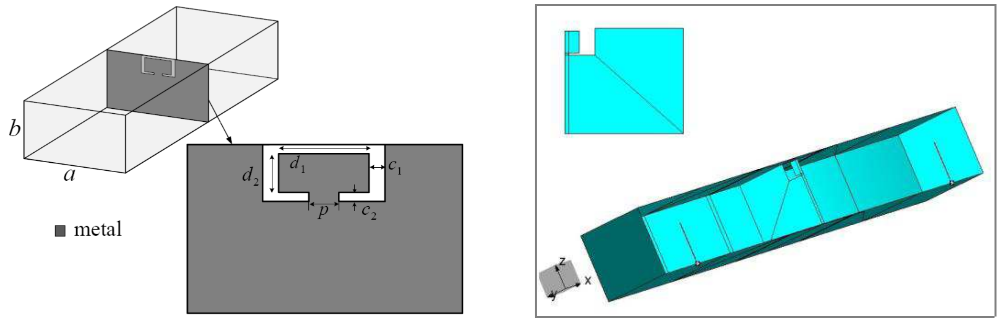
Herein, we propose novel design of the X-band bandpass waveguide filter using the CSRRs. Resonators are implemented as inserts in a form of metal plates, having properly shaped slots, in the transverse planes of the standard WR90 rectangular waveguide, in order to obtain H-plane bandpass waveguide filters. Solutions presented in this paper assume that the resonators are attached to the top and bottom waveguide walls. It is noticed that the resonators implemented in such a manner provide the same resonant frequencies as the ones not attached to the waveguide walls, but they are more compact in terms of dimensions. Filter response is investigated for various parameters of the resonators and their positions. For the filter design and analysis, WIPL-D software [9] is used, as powerful three-dimensional electromagnetic (3D EM) solver capable to perform full-wave simulations.

Proposed design using CSRRs is recognized as scalable solution, applicable for multi-band waveguide filter design. Relatively simple implementation of dual-band filter is introduced, along with the model of the second-order dual-band filter.

2. BANDPASS WAVEGUIDE FILTER USING ONE CSRR

Design starts from the model using insert in a form of flat metal plate with a resonator attached to the top waveguide wall. The three-dimensional electromagnetic model of the filter is depicted in Fig. 1. The parameters of the CSRR are tuned in order to obtain resonant frequency of 11 GHz. According to Fig. 1(a), for the resonator with $f_0 = 11\,\text{GHz}$ dimensions of the CSRR are as follows: $d_1 = 2.8\,\text{mm}$, $d_2 = 2.1\,\text{mm}$, $c_1 = 1.5\,\text{mm}$, $c_2 = 0.25\,\text{mm}$, $p = 0.8\,\text{mm}$.

For the filter design, the standard WR90 rectangular waveguide of width $a = 22.86\,\text{mm}$ and height $b = 10.16\,\text{mm}$ is used. Considered waveguide filters are excited by means of properly modeled ports with quarter-wave probes. It is assumed that the dominant mode of propagation is the transverse electric TE_{10} mode. Discontinuities inside the waveguide are implemented using metal

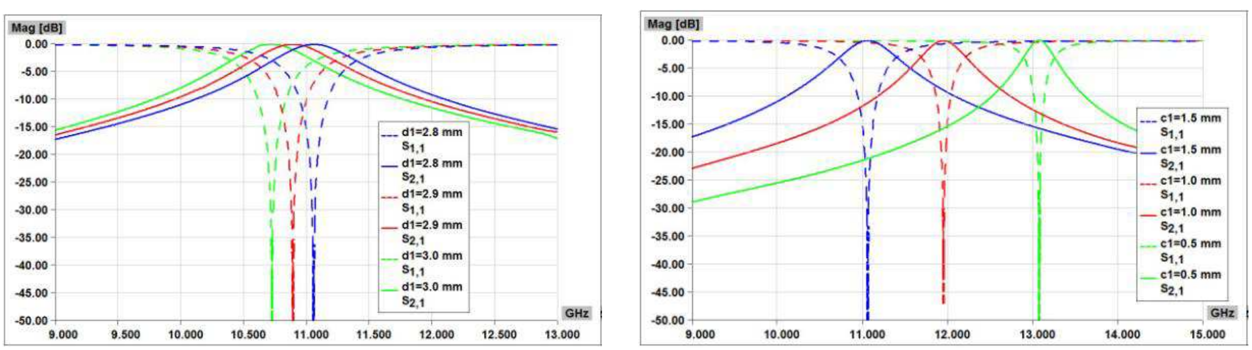


(a) (b)

Figure 1: (a) 3D EM model of the bandpass waveguide filter using one CSRR. (b) WIPL-D model of the bandpass waveguide filter using one CSRR (symmetry applied).

plates, either as flat or folded, with properly shaped slots. These plates are placed in the transverse planes of the described rectangular waveguide. The WIPL-D model of the waveguide filter with one CSRR is shown in Fig. 1(b). The symmetry is used for the filter modeling in WIPL-D software in order to speed up the full-wave simulations. This property significantly reduces the number of unknowns and the CPU time needed to perform the simulation [9].

The frequency response is analyzed for various parameters of the resonator. Comparison of frequency responses, when only one dimension of the CSRR varies, while the others remain unchanged, is shown in Fig. 2. According to the obtained results, it is noticed that the resonator length (e.g., parameter d_1 in Fig. 1(a)) primarily influences the resonant frequency (f_0) while the bandwidth ($B_{3\,\mathrm{dB}}$) is preserved (Fig. 2(a)). On the other hand, variation of resonator width (e.g., parameter c_1 in Fig. 1(a)) introduces the change of both resonant frequency and bandwidth: by decreasing c_1, resonant frequency shifts toward higher values, while the bandwidth becomes narrower (Fig. 2(b)).



(a) (b)

Figure 2: Comparison of filter responses: (a) d_1 varies, $d_2 = 2.1\,\mathrm{mm}$, $c_1 = 1.5\,\mathrm{mm}$, $c_2 = 0.25\,\mathrm{mm}$, $p = 0.8\,\mathrm{mm}$; (b) $d_1 = 2.8\,\mathrm{mm}$, $d_2 = 2.1\,\mathrm{mm}$, c_1 varies, $c_2 = 0.25\,\mathrm{mm}$, $p = 0.8\,\mathrm{mm}$.

Furthermore, the frequency response is analyzed for various positions of the resonator on the metal plate. If the resonator is moved away from the central position, i.e., it is moved to the left or right for the same distance, the response changes similarly: the increase of the distance from the central position results in the narrower bandwidth, while the frequency remains unchanged (Fig. 3).

Finally, the filter response is also investigated when the resonator is attached to the bottom waveguide wall. The obtained result shows no significant change in terms of the resonant frequency and bandwidth, as can be seen in Fig. 4 for the considered example with $f_0 = 11\,\mathrm{GHz}$. To be more precise, the deviation introduced by the change of position is 0.6% for the resonant frequency and 3.2% for the bandwidth, compared to the reference values adopted for the model with CSRR attached to the top wall ($f_0 = 11.069\,\mathrm{GHz}$, $B_{3\,\mathrm{dB}} = 683\,\mathrm{MHz}$).

It should be emphasized that the proposed design of the inserts in the form of metal plates with CSRRs attached to the top and bottom waveguide wall, provides the possibility to have the same resonant frequencies as for the models with CSRRs not attached to the waveguide walls, but

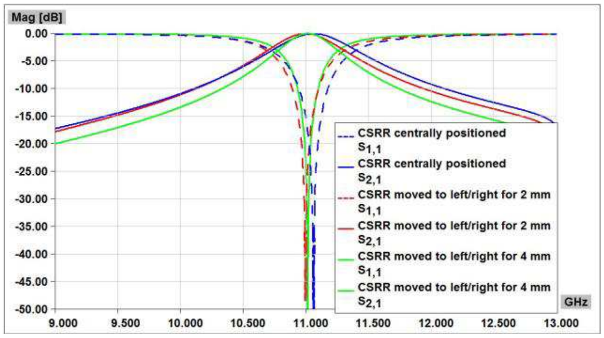


Figure 3: Comparison of filter responses when the resonator is moved away from the central position.

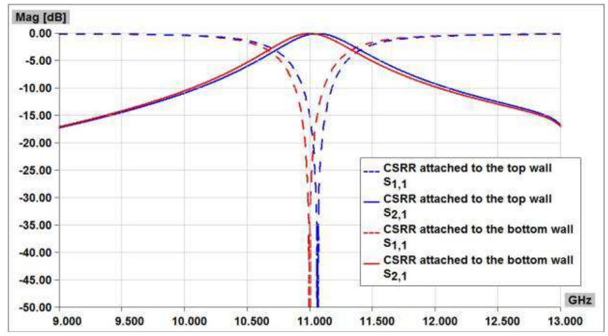


Figure 4: Comparison of filter responses when the resonator is attached to the top and bottom waveguide wall.

with more compact resonators in terms of dimensions. As an example, resonator with $f_0 = 9\,\mathrm{GHz}$ is considered. In case when the resonator is not attached to the waveguide wall, its dimensions are as follows (according to the labels in Fig. 1(a)): $d_1 = 6.0\,\mathrm{mm}$, $d_2 = 23\,\mathrm{mm}$, $c_1 = 1.5\,\mathrm{mm}$, $c_2 = 0.25\,\mathrm{mm}$, $p = 0.8\,\mathrm{mm}$. Therefore, the occupied area can be reduced up to 20% when the resonator is attached to the waveguide wall. Since the resonators occupy less space on the metal insert, it turns out that this approach can be applied for the design of multi-band filters without mutual coupling of the resonators.

3. DUAL-BAND BANDPASS WAVEGUIDE FILTER

As an example of the multi-band filter design using proposed metal inserts, dual-band filter is developed. Considered filter has two central frequencies, $f_{01} = 9\,\mathrm{GHz}$ and $f_{02} = 11\,\mathrm{GHz}$. In order to obtain two frequency bands, flat metal insert is implemented with two CSRRs, one is attached to the top waveguide wall ($f_{01} = 9\,\mathrm{GHz}$) and the other one to the bottom wall ($f_{02} = 11\,\mathrm{GHz}$), as depicted in Fig. 5(a). Dimensions of the resonators, according to Fig. 5(a), are given in Table 1. The same WR90 standard rectangular waveguide is used, as for the model with one CSRR. WIPL-D model of the dual-band filter is shown in Fig. 5(b). The filter response is given in Fig. 6.

As can be seen, relatively simple design provides acceptable solution for dual-band bandpass filter. Since there is no mutual coupling between the resonators on the same plate, each frequency band can be independently controlled by tuning only the corresponding resonator.

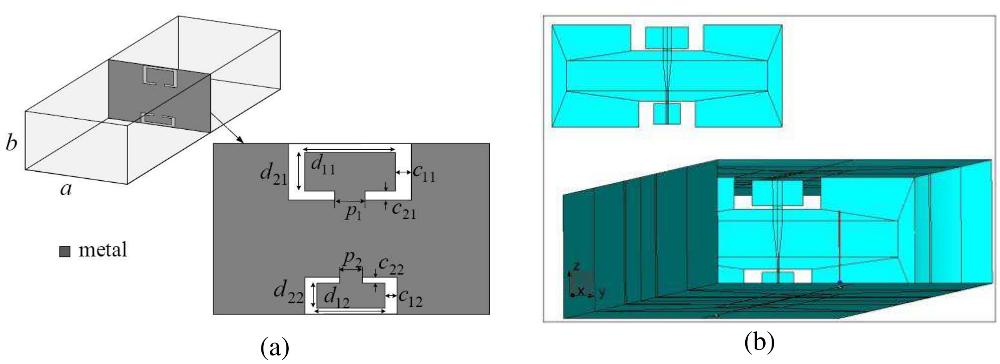


Figure 5: (a) 3D EM model of the dual-band bandpass waveguide filter. (b) WIPL-D model of the dual-band bandpass waveguide filter.

Table 1: Dimensions of the CSRRs used for dual-band filter design.

Dimension	d_{1i} [mm]	d_{2i} [mm]	c_{1i} [mm]	c_{2i} [mm]	p_i [mm]
1st resonator ($i = 1$)	4.25	2.10	1.50	0.25	0.80
2nd resonator ($i = 2$)	2.65	2.10	1.50	0.25	0.20

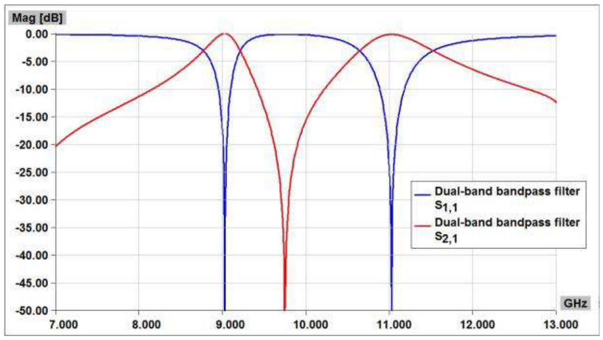


Figure 6: Frequency response of the dual-band bandpass waveguide filter.

4. SECOND-ORDER DUAL-BAND BANDPASS WAVEGUIDE FILTER

Starting from the previously proposed dual-band filter design, second-order bandpass filter is also developed. In this case, folded metal inserts with CSRRs are used in order to implement inverters between the resonators as $\lambda_g/4$ waveguide sections, for each central frequency ($f_{01} = 9\,\mathrm{GHz}$, $f_{02} = 11\,\mathrm{GHz}$). The 3D EM model of the proposed second-order dual-band filter is depicted in Fig. 7(a). Dimensions of the resonators are given in Table 1. According to Fig. 7(a), $l_{pl} = (\lambda_{g9} - \lambda_{g11})/8 = 1.84\,\mathrm{mm}$, $a_{pl} = a = 22.86\,\mathrm{mm}$, $b_{pl} = b/{=}5.082\,\mathrm{mm}$. The second-order dual-band filter model made in software WIPL-D is shown in Fig. 7(b). The obtained filter response is given in Fig. 8.

In order to obtain better matching, i.e., to have lower value for the return loss, proposed model is slightly modified. To be more precise, the plate connecting parts of the folded metal insert with resonators is designed to be narrow, as depicted in Fig. 9(a). All dimensions correspond to those given in Fig. 7(a), except that the width of the plate is set to $w_{pl} = 2\,\mathrm{mm}$. WIPL-D model of the modified filter is shown in Fig. 9(b). The obtained filter response is given in Fig. 10. According to the filter response, the return loss is slightly improved for the second frequency band ($f_{02} = 11\,\mathrm{GHz}$), though at the expense of wider bandwidth. However, the required bandwidth can be obtained by additional modification of the corresponding resonator.

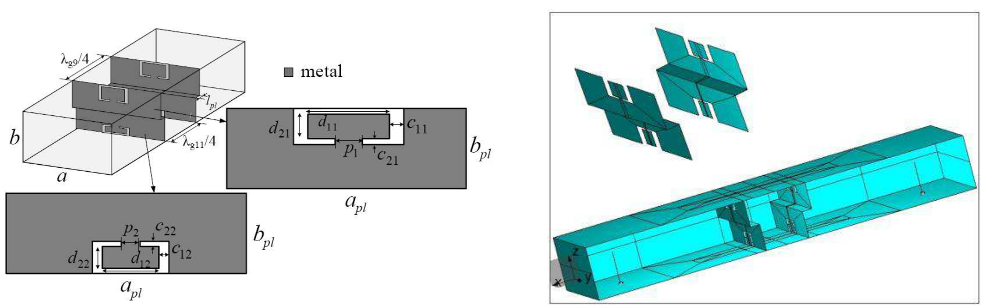


Figure 7: (a) 3D EM model of the second-order dual-band bandpass waveguide filter. (b) WIPL-D model of the second-order dual-band bandpass waveguide filter.

Figure 8: Frequency response of the second-order dual-band bandpass waveguide filter.

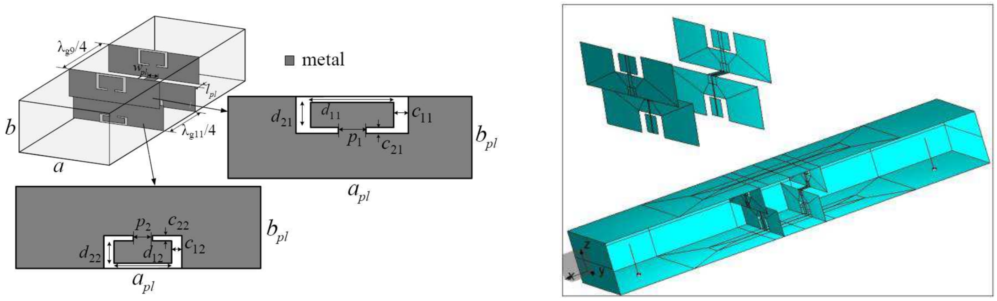


Figure 9: (a) 3D EM model of the modified second-order dual-band bandpass waveguide filter. (b) WIPL-D model of the modified second-order dual-band bandpass waveguide filter.

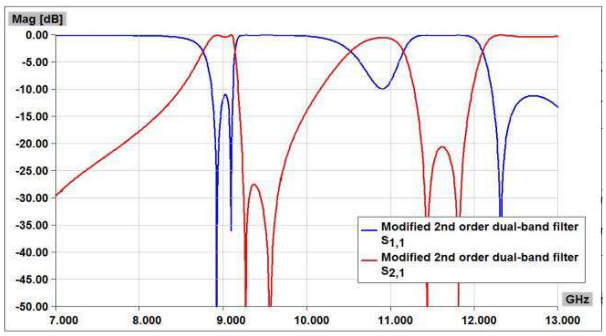


Figure 10: Frequency response of the modified second-order dual-band bandpass waveguide filter.

5. CONCLUSION

Novel design of the H-plane bandpass waveguide filters using CSRRs is proposed. Resonators are implemented as metal inserts with properly shaped slots in the transverse planes of the standard rectangular waveguide. The filter response is investigated for various parameters of the resonators and their positions. The proposed solution with the resonators attached to the waveguide walls provides the same resonant frequencies as the models with resonators not attached to the waveguide walls, but the implementation according to the novel design results in more compact solution (the occupied area on the plate for the resonator can be reduced up to 20%). Also, there is no mutual coupling between the resonators on the same plate. These are important properties for the multi-band filter design. As an example, dual-band bandpass filter is proposed, followed by the second-order dual-band filter. Possible solution for improving the return loss for the second-order dual-band filter is introduced, by slightly modifying the metal inserts without changing the resonators' dimensions. The most important characteristics of the proposed design are simplicity and applicability for multi-band filters, allowing for the higher order filters to be easily developed, as verified in the presented research.

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