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E-PLANE WAVEGUIDE BANDSTOP FILTER WITH DOUBLE-SIDED PRINTED-CIRCUIT INSERT

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Abstract. *In this paper a novel design of an E-plane bandstop waveguide filter with a double-sided printed-circuit insert is presented. Split-ring resonators are used as the resonating elements to obtain the bandstop response. The amplitude response of the waveguide resonator with a single resonating element on the insert is analyzed for various dimensions and positions of the split-ring resonator. The coupling between two resonators on the insert, in terms of their mutual distance, is considered as a next step to the filter design. Various positions of the resonators are considered, including the case with the resonators on the different sides of the insert, which is of interest for the proposed filter design. Finally, a third-order bandstop filter with a double-sided printed-circuit insert, operating in the X-frequency band, is introduced. The filter response is analyzed for various distances between the resonators and for various positions of the resonator printed on the other side of the insert. Proposed filter design is simple, providing for the accurate fabrication, miniaturization and possibility to relatively easy obtain multi-band response, using resonators with different resonant frequencies on the different sides of the insert.*

Key words: *E-plane waveguide filter, bandstop filter, split-ring resonator, double-sided printed-circuit insert*

1. INTRODUCTION

Waveguide filters are widely used components for communication systems operating with high-power signals. They are qualified as passive components with high quality factors and low losses [1]. For example, microwave waveguide filters are elements of various satellite and radar systems, either as bandpass or bandstop filters. E-plane waveguide filters, considered in this paper, are relatively simple to design, fabricate and measure. However, in spite of simple design, there are lots of possibilities to implement

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single E-plane insert using different resonating elements. Various implementations, for different frequency bands, can be found in the available open literature, thus confirming the great interest for the waveguide filters among the researchers in the area of microwave filter design. There are various solutions for the bandpass filter design, using simple or complex resonating elements on the insert. Bandpass filter with ladder-type pattern on substrate, for Ka-band operation, can be found in [2]. An example of the bandpass filter with T-shaped resonator to operate in the X-band is introduced in [3]. Furthermore, rectangular ring resonators (RRRs) are used for the Ka-band bandpass filter design in [4], while the combination of C-shaped and central-folded stripline resonators (CFSRs) for the waveguide filter design is introduced in [5]. For the bandstop filters, solutions with split-ring resonators (SRRs), quarter-wave resonators (QWRs) and other types of simple resonators can be found. Bandstop filters using SRRs with single rejection band are proposed in [6]-[9], while multiple rejection bands are obtained in [10]-[11]. In [12], the authors have exemplified the use of the SRR array for the waveguide filter design. Folded SRRs are used for the third-order Ka-band bandstop filter in [13]. In [14], the possibility to obtain bandpass and bandstop filter response using SRRs with microstrip structures, is explained and illustrated. Second-order bandstop filter with QWRs, combined with SRR as a coupling element, is introduced in [15]. Dual-band E-plane bandstop filter with QWRs is proposed in [16]. Both latter filters are designed to operate in the X-band. Simple rectangular resonating slots are used for single-band and dual-band filter design in [17]. For the E-plane filters with multiple resonating elements on the insert it is important to properly couple them, as explained in [18].

The goal of our research is to design a novel E-plane filter using SRRs. Therefore, we propose a bandstop waveguide filter with a double-sided printed-circuit insert, using SRRs with optimized parameters as the resonating elements, in order to obtain the bandstop response in the X-frequency band (f_0 = 10 GHz). According to the available open literature, waveguide filter design with double-sided printed inserts is still not widespread. So far, several solutions for the waveguide structures with double-sided printed-circuit inserts have been introduced. In [19], the operation of the X-band rectangular waveguide with double-sided single ring resonator array is analyzed in the frequency range 2-10 GHz, in order to investigate the characteristics of metamaterials in the considered waveguides. Furthermore, bandpass filters using various types of resonators (RRRs, C-shaped resonators and CSFRs), printed on different sides of the insert, are proposed in [20], for the W-band, and in [21], for the Ka-band. The bandstop waveguide filter realization, using double-sided printed-circuit insert with SRRs, for the X-band operation, as considered here, represents a novel solution.

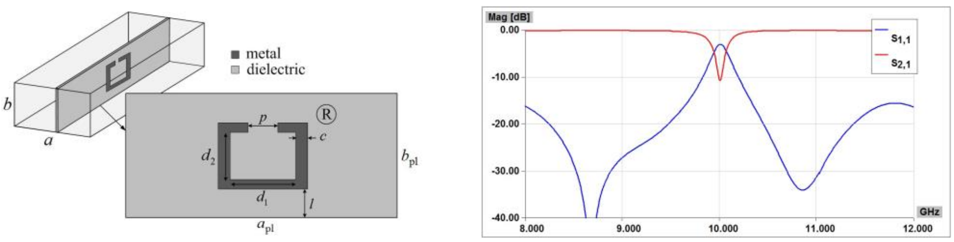
The following steps are carried out to achieve the targeted filter design. The amplitude response of a waveguide resonator using single SRR is analyzed in terms of the dimensions and the position of the SRR. Furthermore, the coupling between two SRRs on the same insert is considered in terms of their mutual distance. Various positions of the SRRs are observed, taking into account the possibility to have SRRs on different sides of the insert, as well. Finally, a novel third-order bandstop filter with a double-sided printed-circuit insert is introduced. The filter response in analyzed in terms of mutual distance between the SRRs and the position of the SRRs printed on the different sides of the insert. WIPL-D software [22] is used to make three-dimensional electromagnetic (3D EM) models of the considered structures and to perform 3D EM full-wave simulations.

The advantage of the proposed design is simple and more accurate fabrication when the distance between the resonators on the insert is critical. Also, the novel design provides possibility to have so-called “overlapped“ resonators, meaning that the SRR on the other side of the insert does not necessarily have to be positioned between the other SRRs, but it may partly overlap with them. Such design contributes to the compactness of the structure, meeting demanding miniaturization requirements in this manner. Another important aspect of the proposed design is possibility to relatively easy obtain multi-band filter response, having resonators with different resonant frequencies on the different sides of the insert.

2. Waveguide Resonator Using E-plane Insert with SRR

The amplitude response of the waveguide resonator using E-plane insert with a single SRR (Figure 1a) is analyzed in terms of the parameters of the SRR and its position. Waveguide resonator and filter, considered in this paper, are designed using standard rectangular waveguide WR-90 (width $a = 22.86$ mm, height $b = 10.16$ mm). They are excited by properly designed ports with probes (monopoles), placed at a distance of $\lambda_g/4$ from the short-circuited end of the port (λ_g – guided wavelength in the waveguide). The TE_{10} mode of propagation is observed. The printed-circuit insert is modeled using copper clad PTFE/woven glass laminate TLX-8 ($\varepsilon_r = 2.55$, $\tan\delta = 0.0019$, $h = 1.143$ mm, $t = 18$ µm). Dimensions of the E-plane insert are $a_{pl} = 22.86$ mm, $b_{pl} = 10.16$ mm. According to Figure 1a, the parameters used for the SRR centrally positioned on the insert are given in Table 1. The obtained amplitude response is shown in Figure 1b ($f_0 = 10$ GHz, $B_{3dB} = 193$ MHz).

The amplitude response is analyzed in terms of dimensions of the SRR and its position. The obtained results are presented in Figure 2 and Table 2.



(a) (b)

Fig. 1 Waveguide resonator using E-plane insert with a single SRR: (a) 3D model, (b) amplitude response

Table 1 Dimensions of the SRR in Figure 1a

Dimension [mm]	d_1	d_2	c	p	l
Value	2.76	2.5	0.4	0.6	3.43

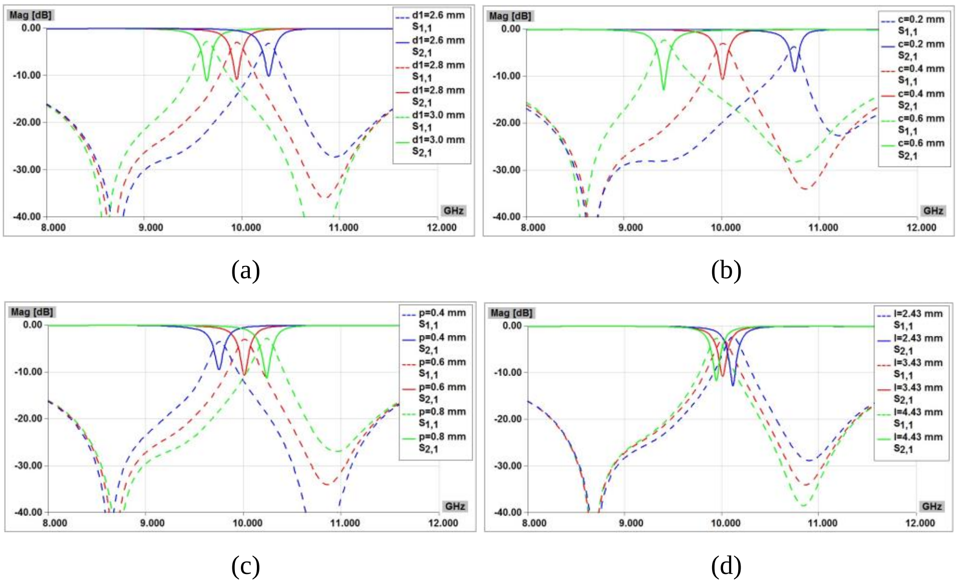


Fig. 2 Comparison of amplitude responses:
(a) d_1 varies, (b) c varies, (c) p varies, (d) l varies

Table 2 Comparison of amplitude responses for single SRR

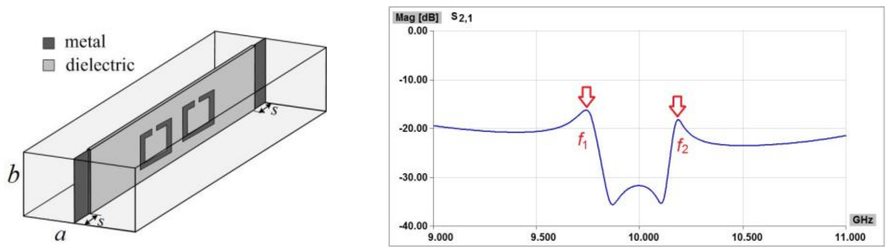
d_2 = 2.5 mm, c = 0.4 mm, p = 0.6 mm, l = 3.43 mm			d_1 = 2.76 mm, d_2 = 2.5 mm, p = 0.6 mm		
d_1 [mm]	f_0 [GHz]	B_{3dB} [MHz]	c [mm]	f_0 [GHz]	B_{3dB} [MHz]
2.6	10.276	190	0.2	10.748	174
2.8	9.945	194	0.4	10.009	193
3.0	9.641	192	0.6	9.408	209
d_1 = 2.76 mm, d_2 = 2.5 mm, c = 0.4 mm, l = 3.43 mm			d_1 = 2.76 mm, d_2 = 2.5 mm, c = 0.4 mm, p = 0.6 mm		
p [mm]	f_0 [GHz]	B_{3dB} [MHz]	l [mm]	f_0 [GHz]	B_{3dB} [MHz]
0.4	9.750	193	2.43	10.115	183
0.6	10.009	193	3.43	10.009	193
0.8	10.238	193	4.43	9.944	178

Variation of resonator length (d_1) primarily influences resonant frequency (longer printed resonator provides lower resonant frequency), while the 3-dB bandwidth practically does not change. Similarly, the increase of the gap width (p) moves the resonant frequency toward higher values, but the bandwidth remains the same. However, the change of the width of the printed trace (c) has the influence on both resonant frequency and bandwidth: by increasing c, f_0 decreases while the band becomes wider, and vice versa. It should be noticed that the change of the trace width c causes small change of l, in order to have centrally positioned SRR regardless of its dimensions. Furthermore, by moving the resonator up and down from its central position on the insert, both resonant frequency and bandwidth change. These results are important for optimization of the parameters and positions of the SRRs used for the filter design, in order to obtain desired amplitude response.

3. Coupling between two SRRs Differently Positioned on E-plane Insert

Coupling between two SRRs on the same E-plane insert, depending on their mutual distance, is analyzed for several different cases. Namely, possible solutions assume various orientations of the SRRs in terms of gap position, and also various positions of the SRRs, i.e. both SRRs can be on the same or different side of the insert. In order to be able to calculate the value of the coupling coefficient, the amplitude characteristic S_{21} [dB] is observed when the resonators are practically decoupled from the ports, meaning that the excitation is weakened, as proposed in [23]. This is achieved by adding metal plates ($s = 8$ mm), on both ends of the insert, toward the ports (Figure 3a). Therefore, two characteristic frequencies (f_1 and f_2), denoting local maxima of the S_{21} characteristic (Figure 3b), are obtained and used for the coupling coefficient k calculation, according to the following formula [24]:

$$k = \frac{f_2^2 - f_1^2}{f_1^2 + f_2^2}. \tag{1}$$



(a) (b)

Fig. 3 Method of determining coupling coefficient:
(a) 3D model with additional metal plates,
(b) S_{21} characteristic with two local maxima

The inserts with two SRRs considered for the coupling analysis are shown in Figure 4. The SRRs depicted using dashed lines are printed on the other side of the insert. Both SRRs have the same dimensions, given in Table 1. However, for cases 1 and 2, $l_1 = l_2 = 3.43$ mm, and for case 3 $l_1 = 3.43$ mm and $l_2 = 3.30$ mm. Figure 5 shows coupling coefficient k as a function of the distance D between the SRRs. For all considered cases, coupling gets weaker (i.e. k decreases) by increasing the distance D. For cases 1 and 2, coupling between resonators is stronger compared to case 3, so it is analyzed for wider range of values of the distance D. It can be noticed that the coupling is pretty much the same for cases 1a and 1b, meaning there is no significant difference whether the SRRs are printed on the same or different sides of the insert. However, for $D \leq 2$ mm, there is significant difference between values of the coupling coefficient obtained for case 2a and 2b. The same stands for case 3a and 3b, for $D \leq 1$ mm. Also, when both SRRs are on the same side of the insert, the strongest coupling is obtained for case 2. On the other hand, when the SRRs are printed on the different sides of the insert, cases 1 and 2 provide stronger coupling, compared to case 3, for the same distance D.

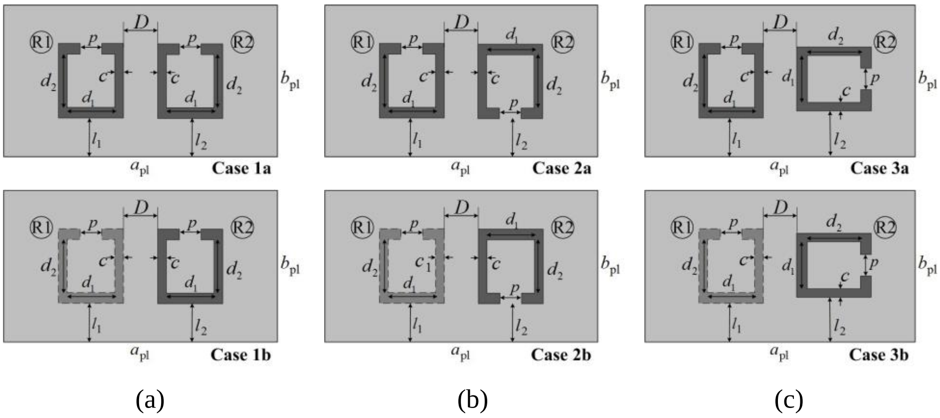


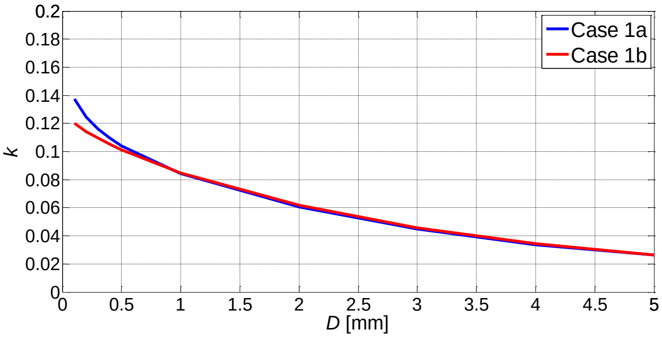
Fig. 4 SRR inserts used for coupling analysis: (a) case 1, (b) case 2, (c) case 3

4. E-PLANE BANDSTOP FILTER WITH DOUBLE-SIDED PRINTED-CIRCUIT INSERT USING SRRS

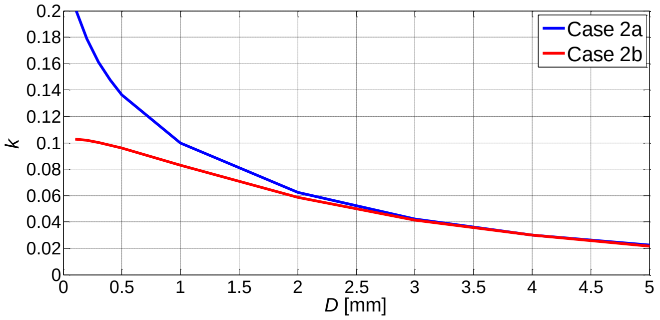
Based on the aforementioned results, a third-order bandstop filter is developed using double-sided printed-circuit insert with SRRs. Two SRRs are printed on the same side of the insert, and the third one (central SRR) is printed on the other side (depicted using dashed line in Figure 6a). The parameters of the SRRs are given in Table 3. Dimensions of the insert are a_{pl} = 22.86 mm, b_{pl} = 10.16 mm. The amplitude response of the proposed filter, for the distance D = 11 mm, is shown in Figure 6b (f_0 = 10 GHz, B_{3dB} = 277 MHz). The total length of the proposed filter is 0.456 λ_g.

The amplitude response of the filter is analyzed for various values of the distance D between two outer SRRs. According to the amplitude responses shown in Figure 6c, it is notable that the increase of the distance D results in a narrower bandwidth, while the center frequency remains practically the same.

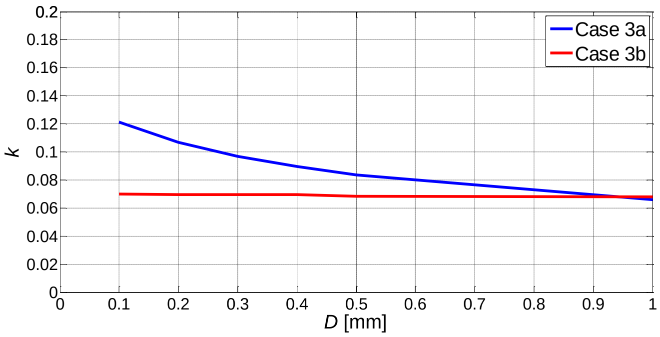
Furthermore, the influence of the position of the central SRR on the filter response is investigated, as well. Considered SRR can be centrally positioned on the insert, as previously proposed, but it can be also shifted up and down, so it does not have to be in line with the outer SRRs (Figure 7a). The obtained amplitude responses, for various values of the shift, are compared as shown in Figure 7b. By moving central SRR up or down for 1 mm, there is no significant change of the center frequency (less than 1 %). However, the 3-dB bandwidth is notably changed, particularly when the SRR is moved up (in the considered case, 3-dB bandwidth is increased for 45 %). This property of the filter can be used for bandwidth tuning.



(a)

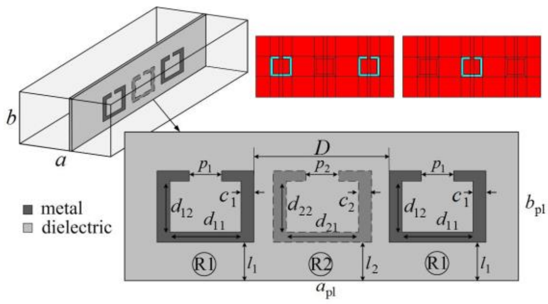


(b)

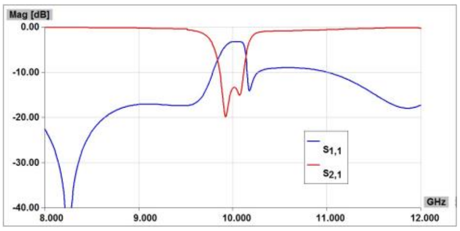


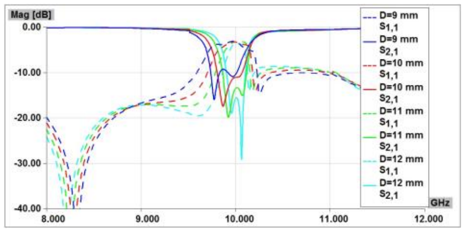
(c)

Fig. 5 Coupling coefficient *k* as a function of distance: (a) case 1, (b) case 2, (c) case 3



(a)



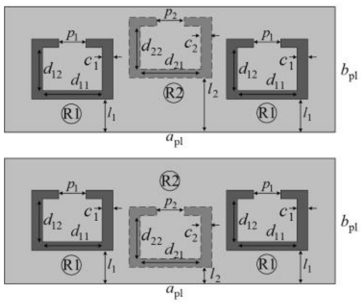


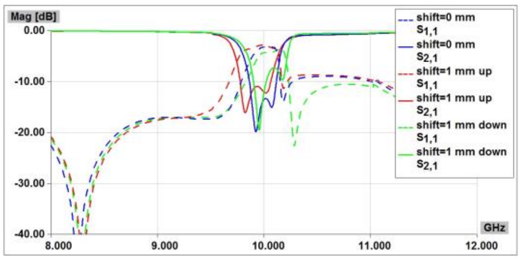
(b) (c)

Fig. 6 Waveguide filter using E-plane insert with SRRs:
(a) 3D model and WIPL-D model of the insert, (b) amplitude response,
(c) comparison of amplitude responses for various values of distance D

Table 3 Dimensions of the SRRs in Figure 6a

Dimension [mm]	d_{i1}	d_{i2}	c_i	p_i	l_i
R1 (i = 1)	2.76	2.5	0.4	0.6	3.43
R2 (i = 2)	2.77	2.5	0.4	0.6	3.43





(a) (b)

Fig. 7 Waveguide filter using E-plane insert with shifted central SRR: (a) models of the insert, (b) comparison of amplitude responses for various values of the shift

Figure 8 shows comparison of amplitude responses of the filter with double-sided printed-circuit insert (Figure 6a), and the one when all three SRRs are printed on the same side of the insert. For both cases, dimensions of the corresponding SRRs are the same, as well as the distance between them ($D = 11$ mm). As can be seen, there is no significant change of the filter response; resonant frequency is the same, while the bandwidth is narrowed for 10 MHz, which is 3.6 % of the reference bandwidth. However, a novel solution with SRRs printed on both sides of the insert allows more accurate fabrication when the distance between the printed traces is critical, so the SRRs can be closer to each other or can even overlap. In this manner, the requirements regarding device miniaturization can be easily met. Also, multi-band filters can be developed having SRRs with different resonant frequencies on the different sides of the insert, occupying less space compared to the solution when the SRRs are printed on the same insert, next to each other, but separated enough to avoid undesired coupling.

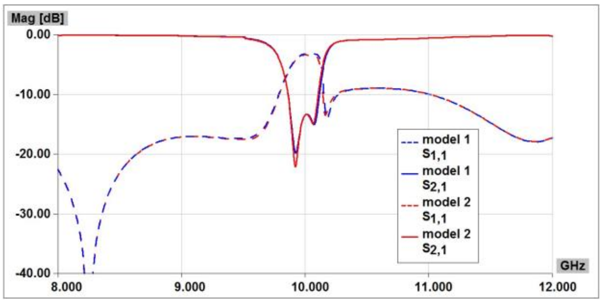
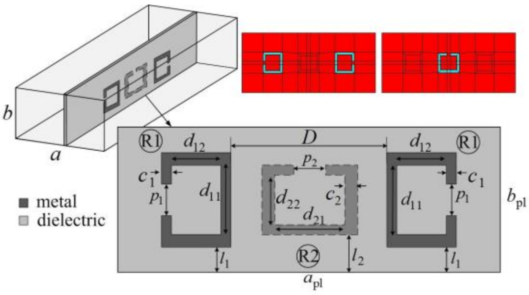


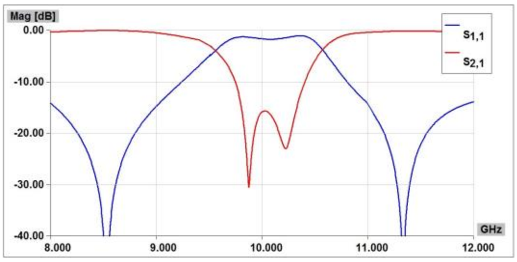
Fig. 8 Comparison of amplitude responses of E-plane bandstop filters with SRRs (model 1: double-sided printed-circuit insert, model 2: single-sided printed-circuit insert)

Another possible solution with double-sided printed-circuit insert is shown in Figure 9a. The outer SRRs are oriented in such manner so their gaps are positioned on the left/right side. Similarly as in the previous examples, the central SRR is printed on the other side of the insert. Dimensions of the SRRs are given in Table 4. The distance between the outer SRRs is set to $D = 9$ mm. The filter length is equal to 0.392 λ_g. The amplitude response of the filter is shown in Figure 9b ($f_0 = 10$ GHz, $B_{3dB} = 1027$ MHz). As can be seen, a wide-band filter is obtained, using the proposed simple approach.

The proposed filters are compared to the similar solutions from the available open literature (E-plane filters of the third order, with a single rejection band), in terms of the filter size on the printed insert. The filter given in Figure 9a exhibits a smaller size than the Ka-band filter presented in [13], whose length is 0.406 λ_g, while each of the filters given in Figures 6a and 9a is shorter than filter in [7] (total length 0.501 λ_g) and X-band filters in [8] (total length 0.572 λ_g) and [17] (total length 1.766 λ_g). Therefore, it can be concluded that the compact structures are designed, with the possibility for further miniaturization. The filter order can be easily increased by adding resonators.



(a)



(b)

Fig. 9 Waveguide filter using E-plane insert with SRRs of various orientations: (a) 3D model and WIPL-D model of the insert, (b) amplitude response

Table 4 Dimensions of the SRRs in Figure 9a

Dimension [mm]	d_{i1}	d_{i2}	c_i	p_i	l_i
*R*1 (i = 1)	2.8	2.5	0.4	0.6	3.28
*R*2 (i = 2)	2.76	2.5	0.4	0.6	3.43

5. Conclusion

Novel design of an E-plane bandstop waveguide filter using a double-sided printed-circuit insert with SRRs has been proposed. Design has started with a model of the waveguide resonator using single SRR. The amplitude response has been thoroughly investigated in order to be able to optimize the parameters of the SRRs for the filter design. The coupling between two SRRs on the insert has been analyzed for various positions of the SRRs and their orientation. Since the double-sided printed-circuit insert is of interest for the presented research, the model with SRRs printed on different sides has been also taken into account. For each considered case, it has been shown that the coupling becomes weaker as the distance between the SRRs increases. Based on these findings, the third-order E-plane filter with the double-sided printed-circuit insert is introduced. The amplitude response has been investigated in terms of the distance between the SRRs and position of the central SRR. By moving the central SRR up or down the bandwidth can be tuned. It has been shown that the amplitude response of the filter with the double-sided printed-circuit insert matches relatively good with the response of the filter with all SRRs printed on the same side of the insert. However, the advantage of the novel solution has been recognized in the fact that printing resonators on different sides of the insert allows more accurate fabrication when the distance between the traces is critical, so the SRRs can be closer to each other. Proposed filter design provides the possibility to have various combinations of the resonators on the insert, resulting in different responses. In this manner, a wide-band filter using double-sided printed-circuit insert with SRRs has been also introduced.

Besides the abovementioned advantage regarding fabrication precision, the proposed filter design allows overlapping resonators printed on the different sides of the insert, therefore providing for the device miniaturization. Also, double-sided printing allows development of multi-band filters using single E-plane insert, having resonators with different resonant frequencies on the different sides of the insert. Such layout of the SRRs occupies less space on the insert, compared to the design assuming SRRs on the same side, next to each other, separated enough to avoid undesired coupling of different bands. Comparison with the similar solutions found in the available open literature has confirmed the proposed filter design in terms of the possibility for device miniaturization. It has been shown that the filters presented here occupy less space on the inserts than some previously reported filters of the same order, operating in different frequency bands, assuming that the filter length is normalized to the guided wavelength in the waveguide for the considered center frequency. The future work will be based on the different implementations of compact multi-band filters using E-plane double-sided printed-circuit inserts, which are recognized as relatively simple to design and fabricate, and can be used in real systems operating at microwave frequencies.

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