A novel design of *E*-plane bandstop waveguide filter using quarter-wave resonators

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A novel design of second-order *E*-plane bandstop waveguide filter is presented in this paper. It is based on the use of properly shaped quarter-wave resonators and a coupling element in a form of split-ring resonator. Actually, quarter-wave resonators are implemented as main resonating elements, while the split-ring resonator is primarily used to fine-tune the rejection-band. Simple design is proposed using single printed-circuit insert, placed in the *E*-plane of the standard WR-90 rectangular waveguide. The obtained filter is intended to operate in X-frequency band, its central frequency is set to 10 GHz, while the bandwidth is nearly 680 MHz. Filter response is investigated for various positions of the resonators, thus elaborating on the effects arising from the change of their positions. The variation of the bandwidth is also explained, regarding the mutual distance between the quarter-wave resonators and the presence of the coupling element. The experimental verification of the proposed design is provided, as well.

1. Introduction

Microwave filters are mandatory components of every modern communication system operating at microwave frequencies. Therefore, the microwave filter design certainly represents attractive research field. Along with the bandpass filters intended to propagate signals at chosen frequencies, bandstop filters are necessary to suppress undesired spurious signals and higher harmonics. For communication systems with demanding operational conditions, such as radar and satellite systems, waveguide filters still represent sustainable solution, in spite of their size and cumbersome structure. One possible approach for waveguide filter design is based on the insertion of discontinuities, variously shaped and positioned in the waveguide [1], without changing the waveguide structure. Solutions with printed-circuit inserts used as discontinuities have been previously reported. These discontinuities actually operate as resonators and they can be designed in a number of ways, placed in the *H*-plane, *E*-plane or both. Some authors propose bandpass filter design using frequency selective surfaces [2-3], or T-shaped resonators [4]. The other types of resonators can be also used: split-ring resonators (SRRs), complementary split ring resonators (CSRRs), quarter-wave resonators (QWRs). Because of their electromagnetic behaviour and a way of exciting, split-ring resonators are used for bandstop filter design, and complementary split-ring resonators for bandpass filter design. The examples of bandstop waveguide filters, using SRRs, with single rejection band can be found in [5-8], and those with multiple rejection bands in [9-13]. Proposed solutions for bandpass filters using CSRRs with single pass band are reported in [14-15], and solutions with multiple pass bands in [16-17]. Bandstop filters with two or three rejection bands, using

quarter-wave resonators are presented in [18]. Depending on the design requirements, the aforementioned resonators can be mutually coupled or distributed on a single printed-circuit board in such a manner that there is no mutual coupling between them. The latter solution provides the possibility to independently tune each resonator, which is important characteristic for multi-band filter design, since each frequency band can be independently controlled, as proposed in [11-13], [16-18].

In this paper, novel design of the second-order *E*-plane bandstop waveguide filter, with possibility to fine-tune the rejection band, is proposed. It is based on the use of properly shaped quarter-wave resonators and a coupling element in a form of split-ring resonator. The main goal of this research is to introduce novel design of bandstop waveguide filter, relatively simple to implement, flexible to manage, and expandable for future applications.

First, frequency response of the filter using single QWR and single SRR on the printed-circuit board in the *E*-plane is investigated for various parameters of these resonators. Further, relatively simple design is proposed using single printed-circuit insert with aforementioned QWRs, placed in the *E*-plane of the standard WR-90 rectangular waveguide. Then, SRR is added between the QWRs, having in mind that the QWRs are implemented as main resonating elements, while the SRR is the coupling element intended to fine-tune the width of the rejection band. The filter is designed to operate in the X-frequency band, its central frequency is set to 10 GHz, while the bandwidth is nearly 680 MHz. Filter response is investigated for various positions of the resonators, thus elaborating on the effects arising from the change of their positions. The variation of the bandwidth is also explained, regarding the mutual distance between the QWRs and the presence of the SRR.

For the filter modelling and analysis, powerful three-dimensional electromagnetic (3D EM) solver is used, so full-wave simulations are performed for the considered structures. The obtained results are also experimentally verified, in order to confirm proposed filter design.

2. Bandstop waveguide filter using single quarter-wave resonator

Since the proposed filter assumes the use of QWRs, design starts with the model of the filter using single QWR, attached to the bottom waveguide wall. In [18], the authors elaborate on the frequency response of the filter implementing printed-circuit insert with QWRs in the *H*-plane of the rectangular waveguide. Here, the printed-circuit is placed in the *E*-plane of the standard rectangular waveguide, as depicted in Fig. 1. The filter is designed to operate with a central frequency of 10 GHz, so the dimensions of the QWR are adjusted accordingly: $d_1 = 2.4$ mm, $d_2 = 1.3$ mm, $c = 0.2$ mm, $p = 0.45$ mm, $l_{str} = 0.5$ mm.
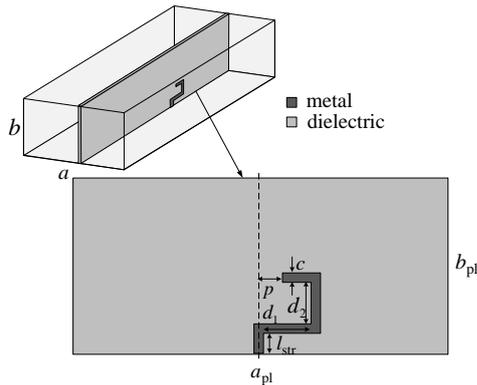
Fig. 1. 3D EM model of the filter using one QWR.

For the filter design, standard WR-90 rectangular waveguide is used, with the following dimensions of its inner cross-section: width $a = 22.86$ mm and height $b = 10.16$ mm, according to Fig. 1. The printed-circuit inserts are implemented using copper clad PTFE/woven glass laminate (TLX-8), with the following parameters from the manufacturer's specification [19]: $\varepsilon_r = 2.55$, $\tan\delta = 0.0019$, substrate thickness $h = 1.143$ mm, metallization thickness $t = 18$ μm. Dimensions of the printed-circuit are $a_{pl} = 22.86$ mm and $b_{pl} = 10.16$ mm. These parameters are used for making the model in WIPL-D software [20]. Also, the conductivity of metal plates is taken into account and it is set to $\sigma = 20$ MS/m. WIPL-D model is shown in Fig. 2a.
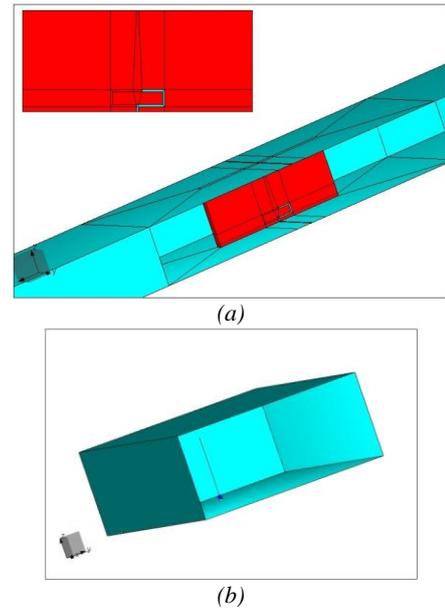
Fig. 2. WIPL-D models:
a) filter using one QWR, b) feeding structure.
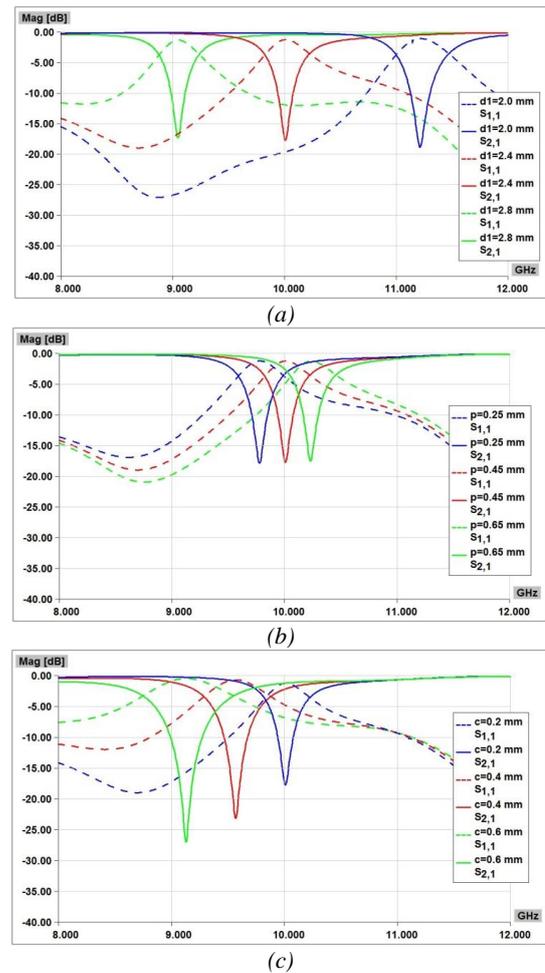
Fig. 3. Comparison of frequency responses for various values of: a) resonator length (d_1), b) distance (p), c) resonator strip width (c).

The waveguide is excited by probes modelled as thin wires with ideal voltage sources (Fig. 2b) and the feeders modelled in this way represent the integral parts of the waveguide structure. However, in order to obtain the frequency response of the filter only, it is necessary to de-embed them from this structure, according to the de-embedding procedure explained in [21]. The dominant mode of propagation is transverse electric TE_{10} mode.

The filter response is investigated for various parameters of the QWR and its position on the plate. In Fig. 3a, the frequency responses are compared for various values of resonator length (d_1). It can be seen that the increase of the resonator length moves the resonant frequency toward lower values and the bandwidth becomes narrower. Further, the filter response is analyzed for various values of the distance (p) and resonator strip width (c). The obtained frequency responses are compared in Figs. 3b and 3c.

The presented results are obtained for the QWR positioned as in Fig. 1. The same frequency response is obtained when the QWR is rotated around the symmetry axis (dashed line in Fig. 1), so this case will not be considered further.

3. Bandstop waveguide filter using single split-ring resonator

The second element relevant for the proposed filter design is SRR on the printed-circuit in *E*-plane (Fig. 4). The filter is designed to operate with a central frequency of 10 GHz, so the dimensions of the SRR, centrally positioned on the plate, are adjusted accordingly: $d_1 = 3.2$ mm, $d_2 = 2.5$ mm, $c = 0.2$ mm, $p = 0.6$ mm. The rectangular waveguide, the substrate of the printed-circuit insert and the feeding structures are the same as for the model given in previous section. Dimensions of the printed-circuit are $a_{pl} = 22.86$ mm and $b_{pl} = 10.16$ mm. This filter is also modelled in WIPL-D software, as shown in Fig. 5.
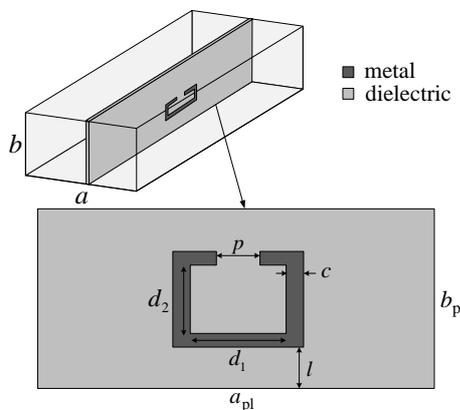
Fig. 4. *3D EM model of the filter using one SRR.*
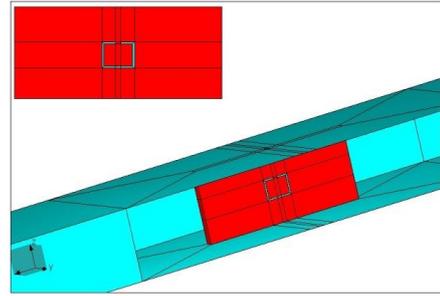
Fig. 5. *WIPL-D model of the filter using one SRR centrally positioned on the plate.*
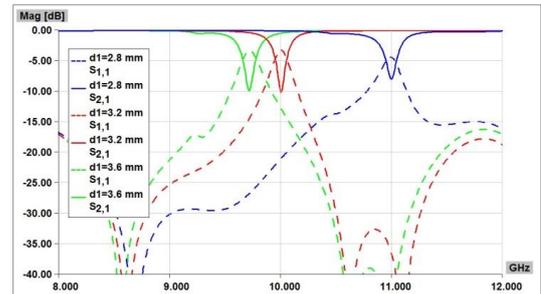
(a)
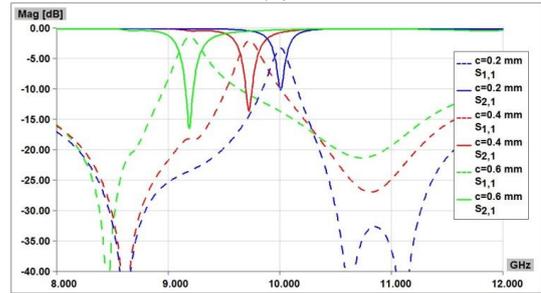
(b)
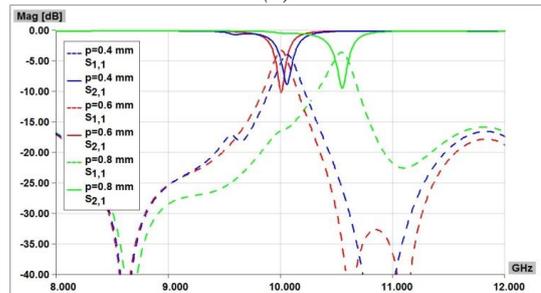
(c)
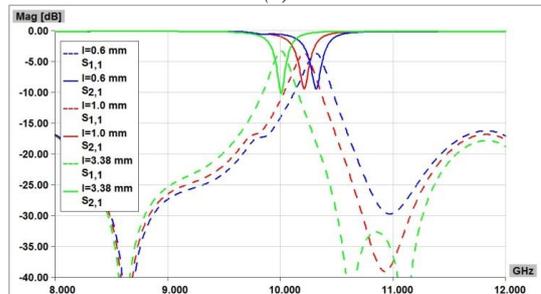
(d)

Fig. 6. *Comparison of frequency responses for various values of: a) resonator length (d_1), b) resonator strip width (c), c) gap width (p), d) distance from the bottom wall (l).*

Similarly as for the model with QWR, the filter response is investigated for various parameters of the SRR and its position on the plate. In Fig. 6, the obtained frequency responses are compared. The increase of the resonator length moves the resonant frequency toward lower values. However, the shortest resonator, with the highest value of the resonant frequency, provides slightly degraded frequency response, as shown in Fig. 6a. Also, the increase of the resonator strip width moves the resonant frequency toward lower values and the bandwidth becomes wider (Fig. 6b). Further, the filter response is analyzed for various values of the gap width (p) and the position of the SRR on the plate, denoted as the distance from the waveguide bottom wall (l in Fig. 4). It can be seen that the excessive increase of the gap width introduces degradation of frequency response (Fig. 6c).

These results are taken into account for the design of the second-order filter, since the SRR is used to fine-tune the bandwidth as explained in the following sections.

4. Second-order *E*-plane bandstop waveguide filter using quarter-wave resonators

The second-order *E*-plane bandstop filter is designed using two QWRs, positioned as depicted in Fig. 7. This filter is designed to operate with central frequency of 10 GHz, and the bandwidth should be nearly 680 MHz. Dimensions of both QWRs are the same, and according to Fig. 7, the following values are used: $d_1 = 2.4$ mm, $d_2 = 1.3$ mm, $c = 0.2$ mm, $p = 0.45$ mm, $l_{str} = 0.5$ mm. The rectangular waveguide, the substrate of the printed-circuit insert, its dimensions, and the feeding structures are the same as for the models with single resonator. The model of the filter, made in WIPL-D software, is shown in Fig. 8. For the chosen distance between the resonators $D = 6.7$ mm, according to Fig. 7, the filter response is given in Fig. 9 ($f_0 = 10.071$ GHz, $B_{3dB} = 678$ MHz).
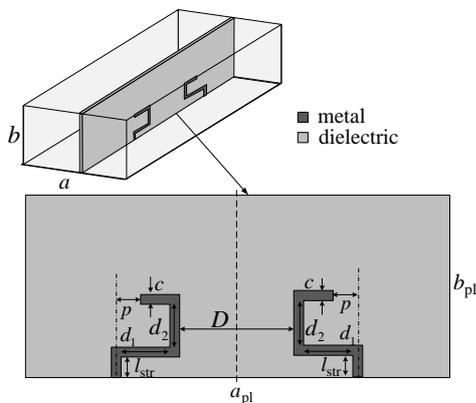
Fig. 7. 3D EM model of the second-order filter using QWRs.

The filter response is analyzed for various values of the distance between the resonators, while keeping their dimensions unchanged ($d_1 = 2.4$ mm, $d_2 = 1.3$ mm,

$c = 0.2$ mm, $p = 0.45$ mm, $l_{str} = 0.5$ mm). Comparison of the obtained frequency responses is given in Fig. 10, and corresponding numerical results are given in Table 1.
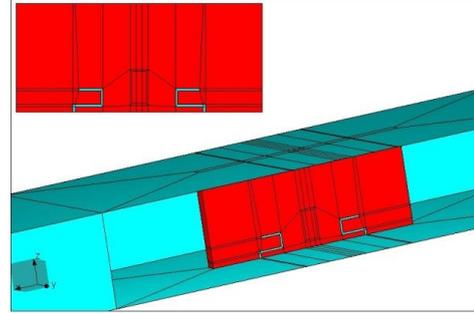
Fig. 8. WIPL-D model of the second-order filter using QWRs.
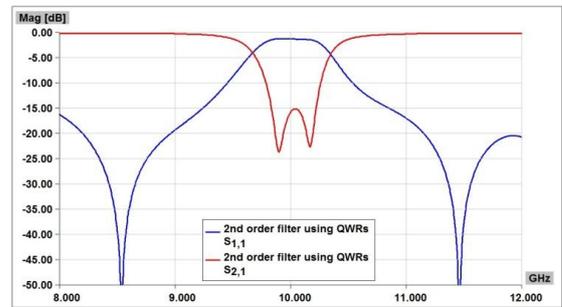
Fig. 9. Frequency response of the second-order E-plane bandstop filter using QWRs.

Table 1. Influence of the distance between the resonators on the frequency response.

D [mm]	f_0 [GHz]	B_{3dB} [MHz]
6.3	10.074	698
6.7	10.071	678
7.1	10.071	664
7.5	10.065	653
7.9	10.059	648
8.3	10.056	643
9.0	10.047	640
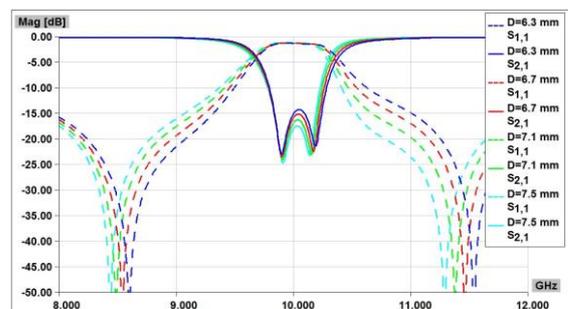
Fig. 10. Comparison of frequency responses for various values of the distance between the QWRs on the plate.

As can be seen, variation of the distance between the QWRs does not introduce significant change of the central frequency. However, it influences the bandwidth, to be more precise, by increasing the distance between the QWRs, the bandwidth becomes narrower.

5. Second-order *E*-plane bandstop waveguide filter using quarter-wave resonators and additional coupling element

The previously introduced model of the second-order *E*-plane bandstop filter is further investigated and new solution for bandwidth fine-tuning is developed by adding SRR between the QWRs. This SRR does not act as resonator, because the idea is to keep the second-order filter. It is primarily used as a coupling element and its resonant frequency does not correspond to the central frequency of the filter. Actually, it is moved to the higher value by properly setting dimensions of the SRR. This novel filter is depicted in Fig. 11. In order to preserve the central frequency of the rejection band, dimensions of the resonators are set to the values given in Table 2. The model of the filter, made in WIPL-D software, is shown in Fig. 12. For the chosen distance $D_1 = 2.5$ mm, according to Fig. 11, the filter response is given in Fig. 13 ($f_0 = 10.065$ GHz, $B_{3dB} = 628$ MHz).
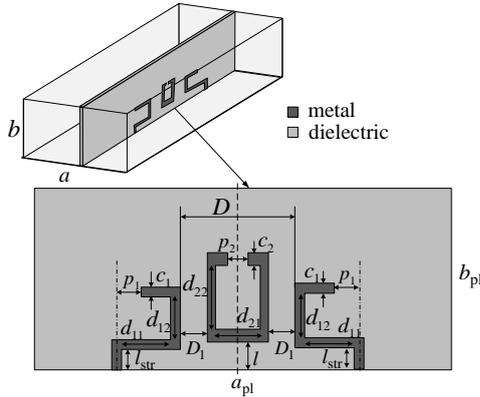
Fig. 11. 3D EM model of the second-order filter using QWRs and coupling element (SRR).
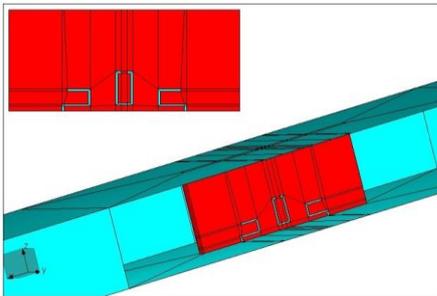
Fig. 12. WIPL-D model of the second-order filter using QWRs and coupling element (SRR).

The frequency responses of the filters with and without SRR are compared (Fig. 14) in order to confirm the influence of the SRR as the coupling element. Numerical results provided in Table 3 show that the change of the central frequency is negligible, but the rejection band is narrowed for 50 MHz (nearly 7.37 % related to the reference value of 678 MHz), as a consequence of inserting the SRR in the middle. It is important to emphasize that the positions of the QWRs are the same as in the model without SRR.

Table 2. Dimensions of the QWRs and coupling element (SRR) in Fig. 11.

Dimension [mm]	QWRs ($i = 1$)	SRR ($i = 2$)
d_{i1}	2.40	1.30
d_{i2}	1.30	3.00
p_i	0.45	0.60
c_i	0.20	0.20
l_{str}	0.50	-
l	-	0.60
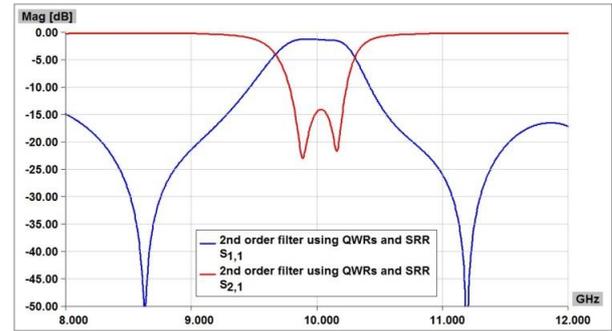
Fig. 13. Frequency response of the second-order E-plane bandstop filter using QWRs and coupling element (SRR).
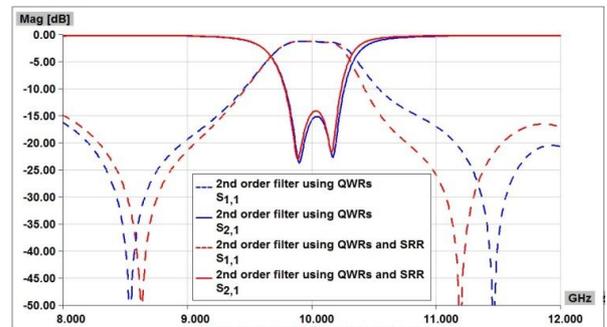
Fig. 14. Comparison of frequency responses for the filters with (red) and without (blue) coupling element (SRR).

*Table 3. Frequency responses of the filters with and
without coupling element (SRR).*

Considered model	f_0 [GHz]	B_{3dB} [MHz]
Filter with QWRs only	10.071	678
Filter with QWRs and SRR	10.065	628

In order to investigate the possibility to fine-tune the bandwidth using SRR, its strip width (c) is varied, causing the variation of the distance between each QWR and SRR (D_1), since the positions of the QWRs remain unchanged (i.e. D does not change). Numerical results regarding the obtained frequency responses are given in Table 4. As can be seen, the aforementioned variation introduces small change of the bandwidth, while the central frequency practically remains the same for each example. Actually, this is in accordance with the expected role of the SRR inserted between the QWRs, because the idea was to add this element to fine-tune the bandwidth and not to change the filter response in any other way, nor to increase the order of the filter.

*Table 4. Variation of the frequency response with
the SRR strip width.*

c [mm]	D_1 [mm]	D [mm]	f_0 [GHz]	B_{3dB} [MHz]
0.1	2.6	6.7	10.065	636
0.2	2.5	6.7	10.065	628
0.3	2.4	6.7	10.067	624
0.4	2.3	6.7	10.068	620
0.5	2.2	6.7	10.069	617
0.6	2.1	6.7	10.070	617

6. Discussion

The obtained results for the proposed solutions can be summarized as follows. The insertion of the SRR between the QWRs narrows the rejection band, as shown in the previous section. In case of the proposed filter, the band is narrowed for 50 MHz (from 678 MHz to 628 MHz, as in Table 3), for the considered parameters of the QWRs and SRR.

According to Table 1, in order to narrow the bandwidth for about 20 MHz (from 698 MHz to 678 GHz), for the filter using QWRs only, it is necessary to increase the distance between them for at least 0.4 mm (from 6.3 mm to 6.7 mm, as in Table 1). On the other hand, the bandwidth can be narrowed for the same value (from 636 MHz to 617 MHz, as in Table 4) if the SRR strip width is increased for 0.4 mm (from 0.1 mm to 0.5 mm), while keeping the same positions of the QWRs, for the filter with QWRs and SRR. However, the latter solution provides the possibility to have more granular variation of the bandwidth by slightly changing only the SRR strip with.

Further, in order to decrease the bandwidth for about 40 MHz (from 678 MHz to 640 MHz, as in Table 1) it is necessary to increase the distance between the QWRs for about 2.3 mm (from 6.7 mm to 9.0 mm), for the filter using QWRs only. The bandwidth can be decreased for the same value (from 678 MHz to 636 MHz) by inserting the SRR using narrow strip (0.1 mm, as in Table 4) between the QWRs, without changing their positions, i.e. there is no need to move them apart to obtain narrower bandwidth. This is also significant result since it has been shown that the insertion of the coupling element provides for filter miniaturization. For example, in order to obtain rejection band of nearly 640 MHz using filter with QWRs only, it is necessary to separate them for 9.0 mm (as in Table 1). However, the same bandwidth can be obtained when the QWRs are mutually separated for 6.7 mm by inserting the SRR with strip width of 0.1 mm between them (as in Table 4). In this manner, the distance between the QWRs is decreased for 2.3 mm, i.e. for nearly 25 % related to the reference value of 9.0 mm in the first case.

It can be noticed that the insertion of the coupling element (SRR) between the QWRs narrows the bandwidth, while the variation of its dimensions provides for fine-tuning of thus obtained bandwidth, without changing the parameters of the QWRs and their positions. This can be useful property for the optimization of filter response, in order to meet the design requirements.

7. Implementation of second-order *E*-plane bandstop waveguide filter using quarter-wave resonators and experimental verification

In order to validate the proposed design, the printed-circuit insert for the filter using QWRs is fabricated (Fig. 15). Available standard WR-90 rectangular waveguide is used and the printed circuit is placed in the *E*-plane of the waveguide. For the measurements, Agilent N5227A network analyzer is used.

Comparison of the obtained simulation and measurement results, for the proposed second-order filter, is given in Fig. 16. As can be seen, these results match relatively good. The obtained results actually confirm that the novel design of the second-order bandstop filter can be validated as acceptable solution.

*Fig. 15. Photograph of the fabricated printed-circuit insert,
with two QWRs, placed in the E-plane of the waveguide.*
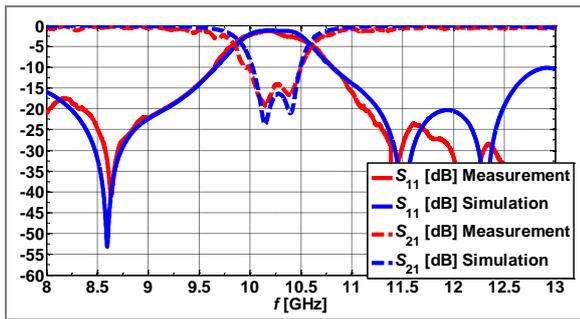
Fig. 16. Comparison of simulation and measurement results for the filter using QWRs.

8. Conclusions

Novel design of the second-order *E*-plane bandstop waveguide filter is presented. For the filter design, properly shaped quarter-wave resonators and a split-ring resonator, as the coupling element, are used. The frequency response of QWR and SRR are investigated in detail, and the obtained results are then used for the second-order filter design.

Simple design is proposed using single printed-circuit insert, placed in the *E*-plane of the standard rectangular waveguide. Two types of printed-circuits are modelled: with QWRs only and with QWRs and coupling element (SRR). QWRs are implemented as main resonating elements, while the SRR is primarily used to fine-tune the rejection band. Filter response is investigated for various positions of the resonators, thus elaborating on the effects arising from the change of their positions. The variation of the bandwidth is also explained, regarding the mutual distance between the QWRs and the presence of the SRR. Actually, insertion of the SRR between the QWRs primarily introduces change regarding the bandwidth. Fine-tuning of the bandwidth, achieved by the proposed design, is recognized as useful property for the optimization of filter response. Also, another advantage is possibility to develop miniaturized structures, since the resonators do not have to be significantly separated to obtain narrowed bandwidth. It is shown that for the rejection band of nearly 640 MHz, mutual distance between the QWRs can be decreased for about 25 % by inserting the SRR between them, for the considered parameters of the QWRs and SRR.

Considered model of the second-order filter using QWRs is fabricated and the obtained experimental results confirm the feasibility of the presented approach.

The authors also conclude that the proposed filter design meets the requirements regarding simplicity of implementation and expandability for future applications.

Acknowledgment

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