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Advanced Filtering Waveguide Components for Microwave Systems

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Abstract

Microwave filter design is a popular topic in the area of modern microwave engineering. Novel technologies, novel applications and more demanding component miniaturization are some of the key drivers for the development of novel microwave filters. For the systems operating with high power and low losses, waveguide filters represent sustainable solutions, in spite of their size. Herein, a method for the advanced bandpass and bandstop waveguide filter design is presented. Properly designed printed-circuit inserts, with simple resonators, are used as resonating elements inside a standard rectangular waveguide. In this manner, multi-band bandpass or bandstop waveguide filters are developed. Multiple resonant frequencies can be obtained using single insert, with properly positioned resonators. Filter design is exemplified by numerous three-dimensional electromagnetic models of the considered structures, equivalent microwave circuits and fabricated devices. Some of the advantages of the proposed design are simplicity, ease of implementation, possibility of miniaturization and experimental verification. The waveguide filters considered here are designed to operate in the X frequency band, so their application is recognized with the radar and satellite systems. Further improvement of the proposed method is possible, according to the future use of the presented devices.

Keywords: bandpass filter, bandstop filter, multi-band filter, waveguide technology, planar inserts, 3D EM modeling and simulation

1. Introduction

Microwave filters are essential components of every modern communication system operating at microwave frequencies. In general, filters are used to pass the signals at chosen frequencies and to block or weaken the undesired signals. Microwave filter design represents an important topic in the area of modern microwave engineering. The researchers are developing novel microwave filters using various technologies, keeping their focus on the novel applications and more demanding device miniaturization, but also bearing in mind the basic filter requirement —to meet a given specification [1].

This chapter focuses on the waveguide filter design. As high quality-factor devices [2], waveguide filters still represent sustainable solutions for the systems where high power and low losses are required (e.g., satellite systems and radar systems).

Waveguide filters can be implemented in different ways. Various solutions based on the waveguide structure modification, by adding branches, are known for decades and are widely implemented. Furthermore, numerous implementations using substrate integrated wave-guide (SIW) technology can be found. Herein, waveguide filters using discontinuities inside the waveguide structure are of interest. These discontinuities can have various shapes and positions [3]. Numerous examples, along with the equivalent circuits and closed-form expressions to calculate the parameters of discontinuities, are given in [4].

In this chapter, waveguide filters using printed-circuit discontinuities are considered. These inserts can be differently positioned inside the waveguide, and some classification can be made accordingly. In the available literature, various solutions can be found for the filters using inserts placed in the E-plane of a rectangular waveguide. Actually, this is a widespread approach, and an example of such design applied to the bandpass filter is presented in [5]. Split-ring resonators (SRRs) are often used as resonating elements for the bandstop filter design. Implementations of bandstop filters using E-plane inserts with SRRs can be found in [6], with a single rejection band, and in [7], with multiple rejection bands. Another approach is based on the use of H-plane inserts. Similarly as for the E-plane insert, various types of resonators can be implemented on the H-plane insert, as well. For the bandpass filters, complementary split-ring resonators (CSRRs) are widely used, as presented in [8, 9], for the filter with a single pass band. Dual-band filter with SRRs is proposed in [10], while compact filter solutions can be found in [11].

The main advantage of the implementations based on the concept of using inserts in the waveguide, compared to the solutions with modified waveguide structure, is simpler design and ease of fabrication.

A method for the advanced bandpass and bandstop waveguide filter design has been devel-oped and reported. It is based on the use of printed-circuit discontinuities, with relatively simple resonators, acting as resonating elements. Multiple resonant frequencies can be obtained using single insert, with properly positioned resonators. The goal is to implement multi-band bandpass or bandstop waveguide filters using printed-circuit inserts, having better characteristics (e.g., bandwidth, return loss, insertion loss and structure size), compared to the

ones published in the available literature. The method considers three-dimensional electro-magnetic (3D EM) modeling of the structures, generating equivalent microwave circuits, optimization and device miniaturization. Relatively simple design, ease of implementation and experimental verification are important aspects of the proposed design guidelines.

The waveguide filters considered here are designed to operate in the X frequency band (8.2–12.4 GHz), so they can be used as components of radar and satellite systems of various purposes. Proposed design method allows their further improvement in accordance with their potential future use. We have been investigated various planar structures, as well, which might be suitable for miniaturization, see for example [12–15].

The chapter is organized as follows. Section 2 will briefly cover waveguide fundamentals, while Section 3 will provide basic concepts of microwave filter design. Section 4 will elaborate on the method for the waveguide filter design, explaining 3D EM modeling and simulation, equivalent microwave circuits and experimental verification of the considered waveguide filters. Sections 5 and 6 will introduce bandpass and bandstop waveguide filters using the presented method for an advanced waveguide filter design, respectively. Section 7 will focus on the multi-band filter design. Finally, the obtained results and findings will be outlined in conclusion.

2. Brief review of waveguide fundamentals

Hollow waveguides represent structures for transmission of electromagnetic waves, consisting of a single transmission line [16]. Depending on the shape of their cross-section, they can be classified as rectangular or circular. Actually, rectangular waveguide is the most commonly used waveguide component [17]. Hollow metal waveguide is a shielded structure, so there is practically no electromagnetic coupling with the surrounding devices. In spite of their size at lower frequencies, they still represent sustainable solution for the systems operating with high power (e.g., transmitters and radars) and low losses (e.g., satellite systems). Also, they can be used for the implementation of high quality-factor resonators.

Rectangular waveguide is used for the transmission of transverse electric (TE) and transverse magnetic (TM) waves. **Figure 1** depicts the rectangular waveguide for the wave propagating along the z-axis. We can assume that the conductor is perfect, while the waveguide is filled by the homogeneous and lossless dielectric. The analysis of the wave propagation assumes solving the wave equation, taking into account the boundary conditions on the waveguide walls.

For the TE wave propagation, with axial electric field $E_z = 0$, it is required to solve the wave equation as a function of H_z, $\Delta_t H_z + K^2 H_z = 0$, or in Cartesian coordinates $\left(\partial^2 H_z / \partial x^2\right) + \left(\partial^2 H_z / \partial y^2\right) + K^2 H_z = 0$, where $K^2 = \gamma^2 + k^2$, $\gamma = j\beta$ is propagation coefficient (β is phase coefficient), $k = \omega\sqrt{\varepsilon\mu}$. Scalar function H_z, given in Cartesian coordinates, $H_z(x, y, z) = H_z(x, y, 0)e^{-\gamma z}$, represents the solution of the given wave equation, and each non-

zero field component can be expressed as a function of H_z. By solving the wave equation, the following expression is obtained for H_z: $H_z(x, y, z) = H_0\cos(m\pi x/a)\cos(n\pi y/b)e^{-j\beta z}$, $m = 0, 1, 2, ...$, $n = 0, 1, 2, ...$, where H_0 is a complex constant. Starting from this solution, the other field components of the TE_{mn} mode can be derived [17].
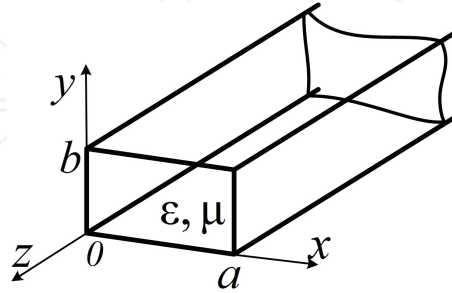

Figure 1. Rectangular waveguide (wave propagation is along z-axis).

Similarly, for the TM wave propagation, with axial magnetic field $H_z = 0$, it is required to solve the wave equation as a function of E_z, $\Delta_t E_z + K^2 E_z = 0$, or in Cartesian coordinates $\left(\partial^2 E_z/\partial x^2\right) + \left(\partial^2 E_z/\partial y^2\right) + K^2 E_z = 0$. Scalar function E_z, given in Cartesian coordinates, $E_z(x, y, z) = E_z(x, y, 0)e^{-\gamma z}$, represents the solution of the given wave equation, and each non-zero field component can be expressed as a function of E_z. The following expression is obtained for E_z, by solving the wave equation: $E_z(x, y, z) = E_0\sin(m\pi x/a)\sin(n\pi y/b)e^{-j\beta z}$, $m = 1, 2, ...$, $n = 1, 2, ...$, where E_0 is complex constant. Starting from this solution, the other field components of the TM_{mn} mode can be obtained, as in [17].

For each TE_{mn} or TM_{mn} mode, the frequency from which that mode starts to propagate, called a cut-off frequency, can be defined as: $f_c = (c/2)\sqrt{(m/a)^2 + (n/b)^2}$ $c = 1/\sqrt{\varepsilon\mu}$.

The wavelength of the guided wave in the waveguide is calculated as: $\lambda_g = \lambda_0/\sqrt{1 - \left(f_c/f\right)^2}$, where λ_0 is the wavelength in the vacuum at frequency f. The following equations are used to determine the wave impedance for the TE_{mn} and TM_{mn} mode: $Z_{TE} = \sqrt{\mu/\varepsilon}/\sqrt{1 - \left(f_c/f\right)^2}$, $Z_{TM} = \sqrt{\mu/\varepsilon}\sqrt{1 - \left(f_c/f\right)^2}$.

The dominant mode of propagation is the one with the lowest cut-off frequency. In case $a > b$, the dominant mode is TE_{10}. The propagation of the dominant mode is of interest, and it will be considered throughout the chapter. Its cut-off frequency is $f_{cTE_{10}} = c/2a = 1/(2a\sqrt{\varepsilon\mu})$, and a set of field equations for this mode is: $E_x(x, y, z) = 0$, $E_y(x, y, z) = -j\omega\mu H_0(a/\pi)\sin(\pi x/a)e^{-j\beta z}$, $H_x(x, y, z) = j\beta H_0(a/\pi)\sin(\pi x/a)e^{-j\beta z}$, $H_y(x, y, z) = 0$, $H_z(x, y, z) = H_0\cos(\pi x/a)e^{-j\beta z}$, where $\beta = \sqrt{\omega^2\varepsilon\mu - (m\pi/a)^2 - (n\pi/b)^2}$ denotes the phase coefficient.

Maximum power in the waveguide is limited by the dielectric breakdown, that is, by the critical field in the waveguide. Furthermore, in case the waveguide is not matched to its ports, so there is a reflected wave beside the incident one, the maximum power will be decreased by the value of the reflected power.

For the waveguide filters considered in this chapter, standard WR-90 rectangular waveguide is used. According to **Figure 1**, dimensions of its cross-section are a = 22.86 mm and b = 10.16 mm. The frequency range for this waveguide is 8.2–12.4 GHz. The cut-off frequency for the dominant mode of propagation TE_{10} is 6.56 GHz. Next, higher mode, TE_{20}, starts propagating from 13.12 GHz, which is in accordance with the observed frequency range for this waveguide.

3. Basic concepts of microwave waveguide filter design

This section briefly covers resonators, as building blocks of the filters, and filter design principles, with the focus on the waveguide filters.

3.1. Resonators

The resonators can be characterized as fundamental passive microwave components and basic elements of the frequency selective circuits, such as filters. They are capable to store frequency-dependent electric and magnetic energy [2]. Under ideal circumstances, resonator is electro-magnetically isolated part of the space, without losses, so once excited electromagnetic field can be indefinitely retained [16]. However, in real situations, every resonator loses its energy due to various losses (e.g., losses in conductors and dielectric) and the coupling with the surrounding components, which is usually weak. This means that the energy must be contin-uously added to the resonator, in order to compensate for the losses and maintain the excited field.

The main parameters which qualify a resonator are its resonant frequency and the quality factor (Q-factor). In general, Q-factor reflects the resonator performance [17].

Resonators can be implemented in different ways: for the frequencies up to 1 GHz as LC circuits and for the frequency range 1 MHz–10 GHz as transmission line sections, while for the frequency range 1–100 GHz as waveguide resonators.

Planar resonators can be classified as resonators implemented in planar technologies, such as the microstrip technology. Quarter-wave and half-wave planar resonators are widely used for the filter design, either as short-circuited or opened lossless transmission-line section of electrical length $\theta = \pi/2$ or $\theta = \pi$ (at resonant frequency $\omega_0 = 2\pi f_0$), respectively. Besides the short-circuited quarter-wave resonators (QWRs), we have developed various models of the waveguide filters using SRRs (for bandstop filters) and CSRRs (for bandpass filters). Filters using these resonators can have one or more pass bands or rejection bands [18–24].

3.2. Basic filter design principles

Filters can be defined as frequency selective networks, with two or more ports, used to pass signals at chosen frequencies and weaken other signals (mostly by reflecting them) [16]. Depending on their use, they can be implemented in different ways. However, the filter design procedure is pretty much determined; it consists of several steps which can be classified as follows [1, 16, 25]: specification, approximation, synthesis, simulation model, implementation, study of imperfections and optimization.

Specification represents a set of criteria that a filter should meet [1, 16]. Approximation is a mathematical representation of the frequency response, so the filter specification can be met and the filter itself can be implemented. It is usually given as an attenuation, in dB, for the low-pass filter, and based on that, approximations for the other types of filters can be derived. Some of the most commonly used approximations are Butterworth, Chebyshev, elliptic (Cauer), Bessel and Gaussian function.

Synthesis assumes generating the filter schematic, using ideal elements, which fulfills transfer function given by approximation. Filter simulation model is a filter schematic with real components instead of ideal ones. Filter implementation is actually a laboratory prototype—fabricated device; it is used to experimentally validate the filter response by measurements, in order to evaluate the simulation model and modify it, if necessary. Study of imperfections investigates various parasitic effects caused by the use of real components. Optimization assumes systematic variation of the filter parameters, using some numerical method, in order to meet the specification.

The filter transfer function is the ratio of the Laplace transforms of the output signal and the input signal assuming zero initial conditions, and the filter is treated as a linear time-invariant two-port network. The frequency response is the transfer function on the imaginary axis. Microwave filter response is typically represented by scattering parameters (S-parameters) [16].

Generic representation of the filter as a two-port network is depicted in **Figure 2a**. At the first port, filter is excited by a real generator, with internal resistance, and the second port is terminated by a resistor.
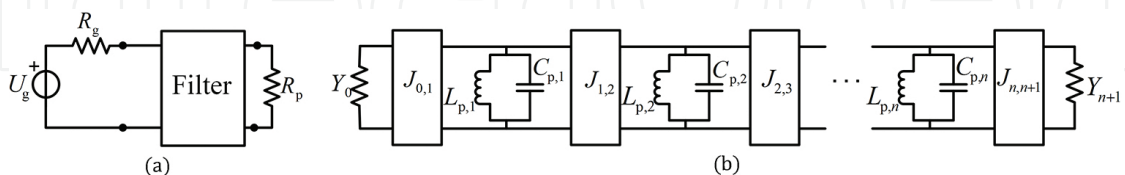

Figure 2. (a) Generic representation of the filter as a two-port network, (b) bandpass filter schematic with parallel LC circuits and admittance inverters.

A filter prototype is a ladder LC network of the low-pass filter with ideal elements. Starting from the prototype, the parameters of the real filter elements can be obtained, by using frequency and impedance transformations [2, 26, 27]. In this manner, bandpass and bandstop filters, consisting of parallel and series LC circuits, can be obtained. Often, it is convenient to

have a network with *LC* circuits only in parallel branches or only in series branches. This can be achieved by adding inverters.

Immittance inverter (a common name for the impedance and admittance inverter) is a two-port, frequency independent, network without losses. Impedance inverter can be used to transform parallel admittance into series impedance, and admittance inverter can be used to transform series impedance into parallel admittance. **Figure 2b** depicts the band-pass filter schematic, with admittance inverters and parallel *LC* circuits. The following equations are used to calculate the characteristic inverter admittance (*J*):

$$J_{0,1} = \sqrt{Y_0 B C_{p,1}/\Omega_{p,\text{proto}} g_0 g_1}, \quad J_{i,i+1} = \left(B/\Omega_{p,\text{proto}}\right)\sqrt{C_{p,i} C_{p,i+1}/g_i g_{i+1}}(i = 1, ..., n-1),$$

$$J_{n,n+1} = \sqrt{Y_{n+1} B C_{p,n}/\Omega_{p,\text{proto}} g_n g_{n+1}}, \quad L_{p,i} = 1/\omega_0^2 C_{p,i} \quad (i = 1, ..., n).$$ Parameters g_i are those used for the prototype filter, as well as $\Omega_{p,\text{proto}}$, while B denotes the bandwidth. The values of the elements Y_0, Y_{n+1}, C_i can be arbitrarily adopted, and the filter response will be identical to the prototype response if the parameters $J_{i,i+1}$ are calculated using afore-mentioned equations.

Immittance inverters can be implemented in different ways. In this chapter, inverters as quarter-wave transmission line sections are of interest. To be more precise, since waveguide filters are considered, inverters are implemented as waveguide sections.

4. Method for advanced waveguide filter design using printed-circuit discontinuities

Advanced waveguide filter design method assumes the development of resonating elements employed as printed-circuit inserts, placed inside a rectangular waveguide [28]. The goal is to obtain one or more resonant frequencies using a single resonating insert, which can be achieved by optimal layout of the resonators on the plate. Desired solution might assume uncoupled resonators, in order to be able to tune each resonator independently for each frequency band. In this manner, multi-band filter can be implemented. Herein, SRRs, CSRRs, QWRs and similar types of simple resonators are used on the printed-circuit inserts as resonating elements.

Waveguide filters can be implemented using H-plane or E-plane inserts. For the higher-order multi-band filters with H-plane inserts, it is necessary to properly implement inverters between the resonators, for each center frequency. For the considered filters, waveguide section of length equal to $\lambda_g/4$ (λ_g – guided wavelength in the waveguide) is used as an inverter. Furthermore, for the higher-order bandpass filter, folded H-plane inserts are used in order to meet require-ment regarding quarter-wave inverter implementation for each center frequency. For the compact filter design, miniaturized inverters are considered, by introducing properly designed additional plates between H-plane resonating inserts. The other solution for the waveguide filter design is based on the E-plane insert implementation, with properly coupled resonators on the plate. Along with the waveguide filter design, structures for precise positioning of inserts are developed and used for the measurement of the frequency responses.

Based on the presented filter design method, an algorithm has been developed, that assumes-following steps: making 3D EM models, optimizing resonator and filter parameters, investigating frequency responses, (optionally) generating microwave circuits and, finally, experimental verification by measuring the response of the fabricated prototype. In order to complete these steps, software tools supporting full-wave simulations have been used, as well as the tools for microwave circuit simulations. Experimental verification is performed to validate simulation results and verify the filter design method.

Various bandpass and bandstop waveguide filters have been developed using proposed method [28, 29]. The same standard rectangular waveguide (WR-90) is used for each implementation in the chosen frequency band, since there is no modification of the waveguide structure. The dominant mode of propagation (TE_{10}) is of interest. Filters are designed to operate in the X frequency band (8.2–12.4 GHz).

For precise modeling of the waveguide filters, WIPL-D software (http://www.wipl-d.com) is used, as powerful software capable to perform EM simulations of the complex 3D structures. It allows us to work with a large number of elements (nodes, plates, generators, etc.) and variables. In terms of numerical calculations, the software is based on the method of moments (MoM), and theoretical background is elaborated in detail in [30]. Besides the network parameters ($S/Z/Y$), it can efficiently calculate near field, far field (radiation) and current distribution.

WIPL-D software provides the possibility of precise geometrical modeling of the structure, meaning it can be completely defined using various elements and parameters available in the software. Virtually, every structure can be modeled in this manner. For example, structures can be modeled as pure metallic, pure dielectric or composite (metallic and dielectric). Every structure primarily consists of nodes, as essential elements, and they are further used to create wires, plates, junctions and generators. As an excitation, an ideal delta-function generator is used. Graphical interface allows us to visually track the modeling procedure.

WIPL-D software provides the possibility to take into account conductor and dielectric losses. The losses due to the surface roughness and the skin effect in conductors are taken into account, so the conductivity of the metal plates, for the X frequency band, is set to $\sigma = 20$ MS/m. Dielectric losses are given as parameters of the domain used to model the considered dielectric.

There are several features in WIPL-D software which can be used to increase the accuracy of the obtained results (edge manipulation) or simplify the modeling procedure (symbols, grids, imaging, symmetry, etc.). All these features are thoroughly explained in the software documentation (http://www.wipl-d.com).

Besides the modeling of the waveguide filter itself, it is important to properly model its excitation, that is, its ports. Each waveguide port (one port on each waveguide end) can be represented as a short-circuited waveguide section with a monopole, fed by an ideal delta-function generator [28]. This section should be long enough so each evanescent mode ceases toward the port end, thus only desired mode propagates in the considered structure. In order to obtain required filter response, that is, to determine its S-parameters, de-embedding

technique is applied, so the influence of the ports on the amplitude response is eliminated. This technique is explained in detail at http://www.wipl-d.com.

In order to generate microwave circuits of the considered filters, the following software tools have been used: WIPL-D Microwave Pro (http://www.wipl-d.com) and NI AWR Microwave Office (http://www.awrcorp.com). The equivalent microwave circuits have been generated using lumped elements (for the resonant circuits) and waveguide sections (for the inverters). The goal is to develop an equivalent circuit as simple as possible, starting from the known equivalent circuits of the corresponding elements, thus allowing for a relatively simple filter optimization.

The printed-circuit inserts are fabricated on the machine MITS Electronics FP-21TP (http://www.mitspcb.com). Experimental verification is performed by measuring the frequency characteristics of the fabricated filters using network analyzer Agilent N5227A (http://www.keysight.com), as shown in **Figure 3**.

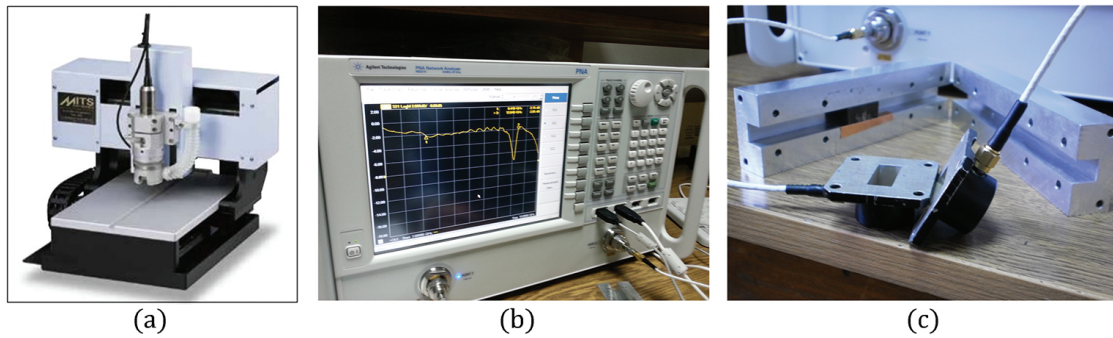(a)   (b)   (c)

Figure 3. (a) MITS Electronics FP-21TP machine, (b) Agilent N5227A network analyzer, (c) ports used for the measurements.

5. Bandpass filters

Bandpass waveguide filter design is based on the use of CSRRs. Starting from the models given in [9], various types of waveguide resonators and filters have been developed and proposed. The inserts are placed in the H-plane of the standard rectangular waveguide. The 3D EM models and equivalent microwave circuit of the CSRR on the multi-layer planar insert can be found in [31, 32]. Such CSRR can be further upgraded by adding a central section on the inner side, providing for resonant frequency fine-tuning, as proposed in [32].

Third-order bandpass waveguide filter has been developed using aforementioned printed-circuit inserts with CSRRs [31]. For the printed circuits, RT/Duroid 5880 substrate (http://www.rogerscorp.com) is used, and its parameters are relative permittivity ε_r = 2.2, losses tanδ = 0.0009, substrate thickness h = 0.8 mm, metallization thickness t = 0.018 mm. The inserts are placed in the transverse planes of the waveguide (**Figure 4a**). Filter is designed to operate at center frequency of 11.95 GHz and 3-dB bandwidth of 500 MHz, so the parameters of the CSRRs

are tuned accordingly. In order to properly design higher-order filter, it is necessary to take into account the inverters between the resonating elements (waveguide sections of length equal to $\lambda_g/4$ at 11.95 GHz). The obtained amplitude response is shown in **Figure 4b**.
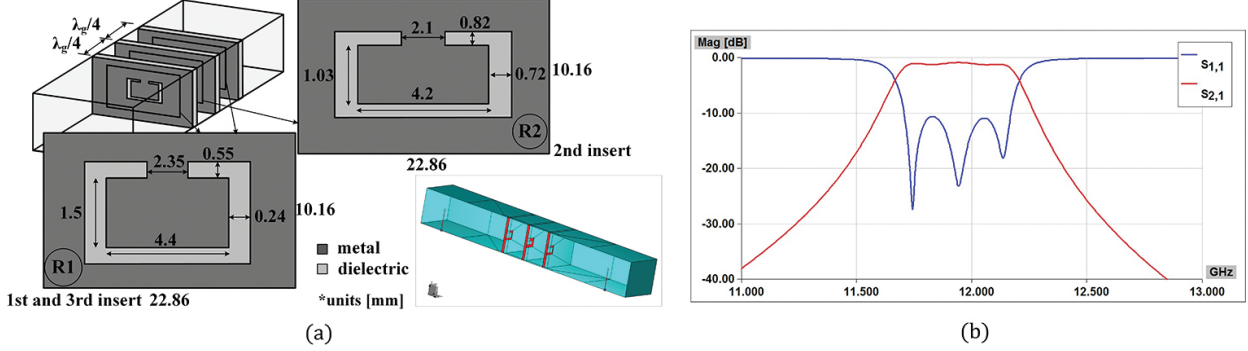

Figure 4. Third-order bandpass filter using CSRRs on the printed-circuit inserts: (a) 3D model, (b) amplitude response.

6. Bandstop filters

Bandstop filters presented here are implemented using SRRs and QWRs on the multilayer planar inserts. Depending on the filter design, the inserts can be placed in the H-plane or E-plane of the rectangular waveguide, as will be elaborated in this section.

The basic model of the waveguide resonator uses printed-circuit insert with dimensions equal to those of the waveguide cross-section (**Figure 5a**, type 1). SRR is used as a resonator. Such model can be found in the available literature [10, 11], and it is also investigated in detail in [33]. Another planar insert with SRR (type 2), introduced in [34, 35], is implemented as a small dielectric plate (it is significantly smaller than the waveguide cross-section), attached to the top and bottom waveguide walls by thin dielectric strips. The waveguide resonator using this type of resonating insert is also shown in **Figure 5a**. In both cases, inserts are designed using RT/Duroid 5880 substrate (its parameters are given in Section 5). Dimensions of the SRR in both cases are optimized to achieve f_0 = 9 GHz. The amplitude responses of the waveguide resonators using previously described inserts are compared in **Figure 5b**. Although resonant frequencies are slightly moved apart, it is notable that the return loss beyond the stop band has lower values for the type 2 insert. Therefore, better matching in the pass band can be obtained using smaller planar insert. This is an important result for the higher-order filter design.

For this model of the resonator, the equivalent circuit is proposed (**Figure 5c**). The parameters of the RLC circuit are calculated using following equations [28]: $R = \left(2\left|S_{11}(j\omega_0)\right|Z_0\right)/\left(1 - \left|S_{11}(j\omega_0)\right|\right), L = \left(2B_{3dB}Z_0\left|S_{11}(j\omega_0)\right|\right)/\omega_0^2, C = 1/\left(2B_{3dB}Z_0\left|S_{11}(j\omega_0)\right|\right),$ where R represents resistance, L inductance, C capacitance, ω_0 is the resonant frequency in [rad/s], $\left|S_{11}(j\omega_0)\right|$ is the amplitude characteristic of S_{11} at resonant frequency, B_{3dB} is a 3-dB

bandwidth, Z_0 represents the nominal impedance and it is calculated according to equations given in Section 2.
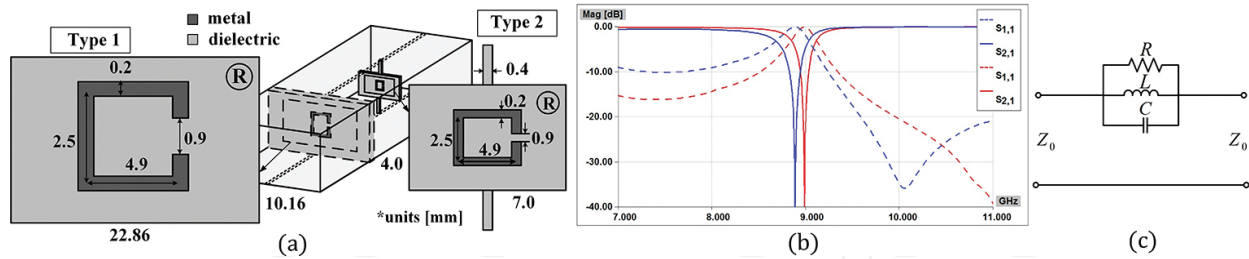

Figure 5. Waveguide resonator using printed-circuit insert with SRR: (a) type 1 and 2, (b) comparison of amplitude responses: blue—type 1 insert, red—type 2 insert, (c) equivalent circuit.

Besides SRRs, properly designed QWRs can be also used for the bandstop filter design. They are short-circuited to top or bottom waveguide wall, depending on the implementation. The insert with the QWRs can be placed in the H-plane [36] or E-plane [37] of the rectangular waveguide.

6.1. Third-order H-plane bandstop filter using printed-circuit insert with SRR

The third-order bandstop filter using aforementioned type 2 planar inserts is shown in **Figure 6a**. Small dielectric plates are centrally positioned in the waveguide. The filter is designed for the center frequency of 9 GHz and the 3-dB bandwidth of 320 MHz, so dimensions of the SRRs are optimized accordingly. The obtained amplitude response is given in **Figure 6b**.
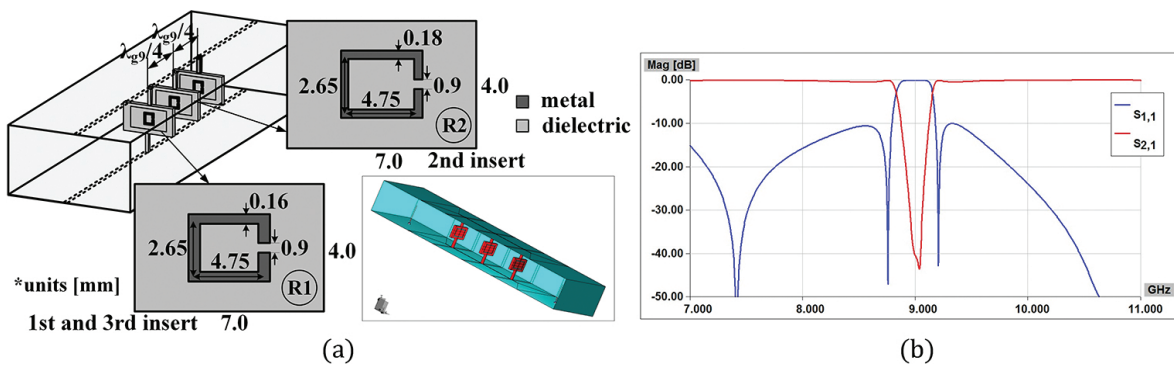

Figure 6. Third-order bandstop filter using printed-circuit insert with SRR (type 2): (a) 3D model, (b) amplitude response.

6.2. E-plane bandstop waveguide filter using QWRs

Herein, second-order bandstop filter using E-plane insert with QWRs is considered. Filter specification requires the center frequency of 10 GHz and 3-dB bandwidth of 680 MHz. Two QWRs, with identical dimensions, are used to achieve this, and they are positioned on the

insert as shown in **Figure 7a**. For the planar insert, copper clad PTFE/woven glass laminate (TLX-8) (http://www.taconic-add.com) is used as a substrate, and its parameters are $\varepsilon_r = 2.55$, $\tan\delta = 0.0019$, $h = 1.143$ mm, $t = 0.018$ mm.

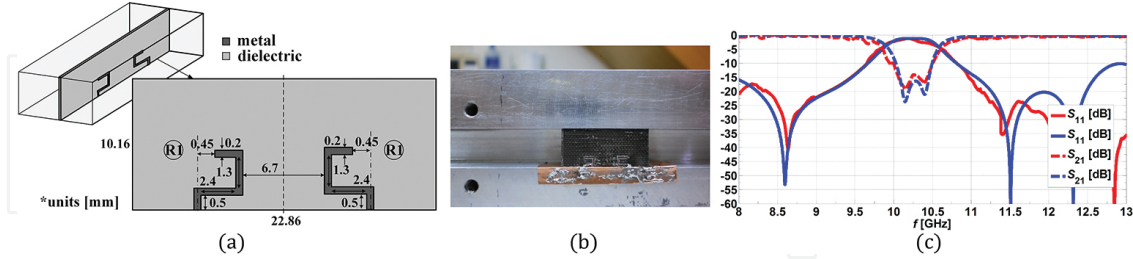(a)   (b)   (c)

Figure 7. Bandstop filter using E-plane insert with QWRs: (a) 3D model, (b) fabricated insert, (c) comparison of amplitude responses: blue—simulation results, red—measurement results.

The amplitude response is analyzed for various values of the distance between the QWRs. It has been shown that this variation primarily influences the bandwidth; to be more precise, by increasing the distance, the bandwidth becomes narrower.

For the considered filter model, the coupling between two QWRs is investigated in terms of their mutual distance, as proposed in [26, 38]. By increasing the distance, the coupling gets weaker. Based on the obtained results for the 3-dB bandwidth and the coupling coefficient k, it can be concluded that these results are in accordance with the statements in the available literature [26], that is, B_{3dB} and k change in the same manner.

In order to validate the proposed design, the planar insert for the filter containing QWRs is fabricated (**Figure 7b**), and the obtained response is experimentally verified using the WR-90 waveguide. **Figure 7c** shows comparison of the simulation and measurement results, and their good matching confirms filter design.

Proposed filter can be further upgraded to achieve bandwidth fine-tuning, by adding a coupling element, realized as a SRR and positioned between the QWRs on the insert (**Figure 8a**). The positions of the QWRs and their mutual distance are the same as in the original model without coupling element. The amplitude response is shown in **Figure 8b**. The obtained results show that, by adding the coupling element between the QWRs, the bandwidth becomes narrower for 50 MHz (which is nearly 7.37% compared to the reference value of 678 MHz for the second-order filter).

In order to investigate the possibility for bandwidth fine-tuning, using the coupling element, its printed line width is varied, while the distance between the QWRs remains the same. In this case, the center frequency practically does not change, while the bandwidth is slightly changed. This is in accordance with the purpose of the coupling element to fine-tune the bandwidth, without modifying the filter response.

Similarly as for the filter with two QWRs, the coupling between the resonators is also analyzed for this case, for the chosen distance between the resonators and different values of the printed line width of the coupling element. The obtained results and conclusions regarding the

proposed filter design can be summarized as follows. By adding the coupling element between the QWRs: (1) the bandwidth is decreased, (2) the coupling is weakened, (3) the bandwidth can be tuned (decreased) without increasing the distance between the QWRs, thus providing for the device miniaturization.
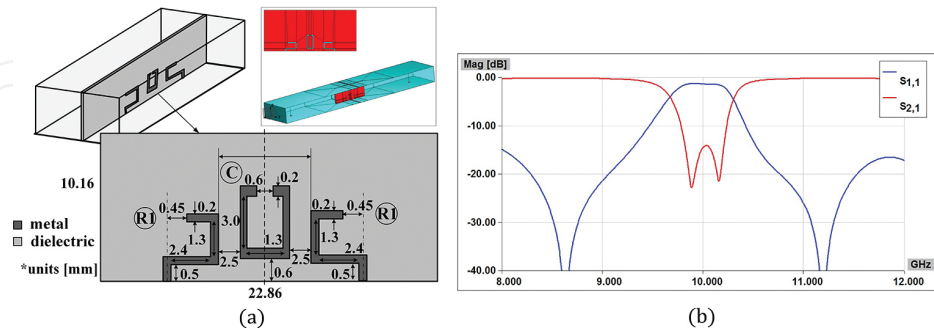

Figure 8. Waveguide filter using E-plane insert with QWRs and coupling element: (a) 3D model, (b) amplitude response.

7. Multi-band waveguide filter design

Multi-band filter design represents a significant research field, particularly for the modern communication systems. One of the advantages of the presented method for the waveguide filter design is that it can be used to relatively easy develop multi-band bandpass or bandstop filters. Namely, multiple resonant frequencies can be obtained using single insert with properly designed and positioned resonators. It is recommended to have uncoupled resonators on the insert, since in that case, each frequency band can be independently controlled by tuning only particular resonator [28]. Waveguide resonator with multiple resonant frequencies can be obtained in this manner. It can be designed using H-plane insert with multiple CSRRs or similar resonating elements for the bandpass characteristic, as in [32, 39–41], or with SRRs for the bandstop characteristic, as in [33, 34]. H-plane insert with QWRs, providing multiple resonant frequencies and having bandstop characteristic, is introduced in [36]. Herein, compact dual-band bandpass filter with CSRRs and dual-band bandstop filter are elaborated in detail. They both use H-plane inserts.

7.1. Compact dual-band bandpass filter with H-plane inserts

Design starts from the resonating insert with two CSRRs in order to obtain two resonant frequencies, 9 GHz and 11 GHz. Flat metal insert with two CSRRs can be placed in the H-plane of the rectangular waveguide, as explained in [40, 41].

Since it is necessary to properly implement inverters for each center frequency, for higher-order filters, folded insert is introduced as a suitable solution [40, 41]. The second-order filter using two identical folded metal inserts is shown in **Figure 9**. Dimensions of the CSRRs are the same for both inserts and optimized to obtain f_{01} = 9 GHz, B_{3dB-1} = 450 MHz, f_{02} = 11 GHz, B_{3dB-2} = 650

MHz. The length of the plate connecting parts of the folded insert with CSRRs is $l_{pl} = (\lambda_{g9GHz} - \lambda_{g11GHz})/8$. In this manner, quarter-wave inverters are implemented for both center frequencies, as shown in **Figure 9a**.
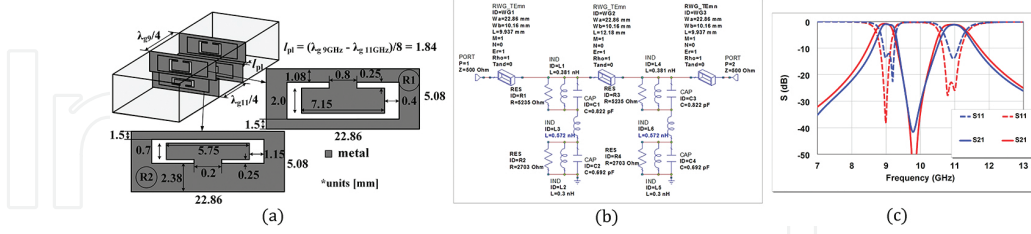

Figure 9. Second-order bandpass filter using folded metal inserts with CSRRs: (a) 3D model, (b) equivalent microwave circuit, (c) comparison of amplitude responses for the 3D EM model (blue) and equivalent circuit (red).

The equivalent microwave circuit is generated for the proposed second-order filter (**Figure 9b**). Two separate networks are used for each insert, and the waveguide section is added between them as a quarter-wave inverter. The short plate providing the fold is represented by an inductor. The following equations are derived [28] and used to calculate the parameters of the *RLC* circuits: $R = \left(Z_0 |S_{21}(j\omega_0)|\right)/\left(2(1 - |S_{21}(j\omega_0)|)\right)$, $L = \left(B_{3dB} Z_0 |S_{21}(j\omega_0)|\right)/\left(2\omega_0^2\right)$, $C = 2/\left(B_{3dB} Z_0 |S_{21}(j\omega_0)|\right)$, where R represents resistance, L inductance, C capacitance, ω_0 is the resonant frequency in [rad/s], $|S_{21}(j\omega_0)|$ is the amplitude characteristic of S_{21} at resonant frequency, B_{3dB} is a 3-dB bandwidth, Z_0 represents the nominal impedance and it is calculated according to equations given in Section 2. The inductances of the additional inductors between *RLC* circuits, for each insert, are tuned. The port impedance is set to Z_0 = 500 Ω, which is the wave impedance at 10 GHz (the frequency between the targeted ones, 9 GHz and 11 GHz). The amplitude responses obtained for the 3D EM model and circuit are compared in **Figure 9c**, and their good mutual agreement validates proposed equivalent representation.

The next step is to develop compact solution, based on the use of miniaturized inverters. Precisely, quarter-wave inverter between the resonating inserts, for each center frequency, is replaced by a shorter waveguide section and additional, properly designed, metal insert. In this manner, the length of the device decreases, by shortening the inverters, without degrading filter response. The realization details, including 3D EM models and the equivalent microwave circuit, of the filter with inverters of length equal to $\lambda_g/8$ for each center frequency, can be found in [40, 41]. The inverters are halved compared to the original model, and additional metal plate for miniaturization (with properly designed slots) is centrally positioned between the resonating inserts, to preserve the original filter response.

In order to simplify fabrication and experimental verification, presented filter can be further modified. Therefore, a compact filter with flat inserts is proposed. This means that the inserts with CSRRs, as well as the additional insert for miniaturization, are flat. However, the inverters for both center frequencies are not miniaturized in the same manner. The distance between the CSRRs with f_{01} = 9 GHz is set to $\lambda_{g9GHz}/8$, while the normalized length of the inverter between

the CSRRs with f_{02} = 11 GHz is equal to $0.18\lambda_{\mathrm{g11GHz}}$ (**Figure 10a**). Dimensions of the slots on the additional metal insert are tuned to preserve the original filter response, without miniaturization. Comparison of amplitude responses of the second-order dual-band filter before and after applying inverter miniaturization, with the same and different normalized lengths of the inverters, is shown in **Figure 10b**. Since the obtained results match well, compact filter with flat inserts is confirmed as a solution more suitable for experimental verification.
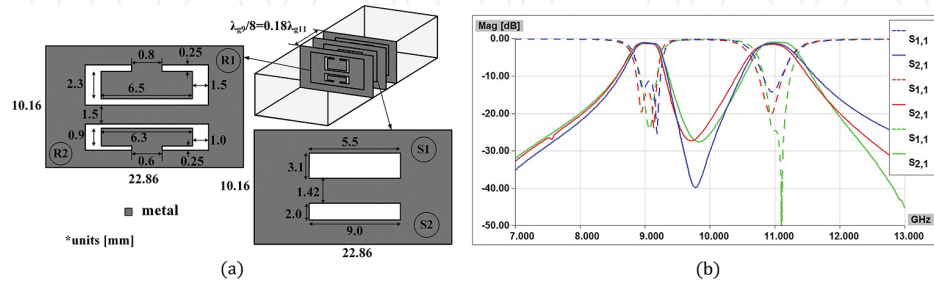

Figure 10. (a) Compact bandpass filter with unequal inverter miniaturization, (b) comparison of amplitude responses of the filter without inverter miniaturization (blue), with equal (red) and unequal (green) inverter miniaturization.

In order to confirm the proposed compact filter solution, the amplitude response of the second-order dual-band filter with flat metal inserts and unequal inverter miniaturization is experimentally verified. Resonating inserts and additional plate for miniaturization are fabricated using metal foil of thickness 100 μm. However, it is necessary to have stable inserts inside the waveguide to successfully measure the amplitude characteristics. Therefore, we propose fixtures for supporting metal inserts. They are fabricated using FR-4 epoxy substrate (ε_r = 4.5, h = 1.0 mm, tanδ = 0.02). Structures for precise positioning of inserts are depicted in **Figure 11a**, and the detailed description of their design can be found in [41]. The photographs of the fabricated inserts and the structures for precise positioning are given in **Figure 11b**. Comparison of the simulated and measured amplitude responses is shown in **Figure 11c**, confirming the compact filter solution by a good agreement of the obtained results.
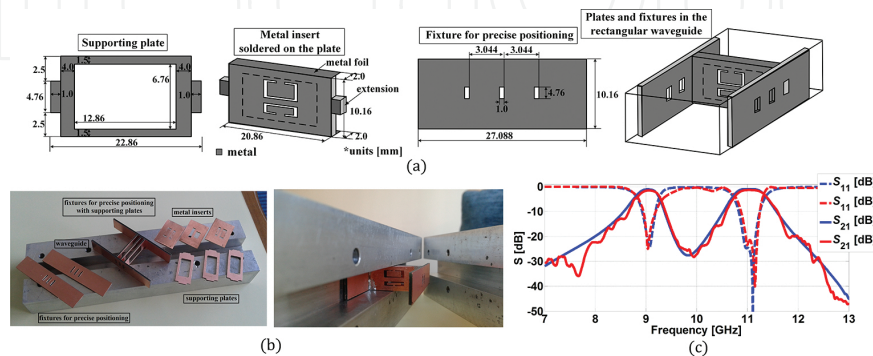

Figure 11. Experimental verification: (a) structures for precise positioning of inserts, (b) photographs of the fabricated components, (c) comparison of simulated (blue) and measured (red) amplitude responses for the compact filter.

7.2. Third-order dual-band bandstop filter using planar insert with SRR

Herein, third-order bandstop filters using printed-circuit inserts with SRRs, introduced in Section 6, are considered. In this manner, the use of such inserts for the higher-order multi-band filters is exemplified. First, third-order bandstop filters with f_0 = 9 GHz and f_0 = 11 GHz, each having a single rejection band, are designed. Based on that, by combining elements of these single-band filters, third-order dual-band filter is designed with f_{01} = 9 GHz and f_{02} = 11 GHz, and each rejection band has the same 3-dB bandwidth of 335 MHz [35].

For the bandstop filter, it is convenient to have *LC* circuits, representing resonators, connected in series; thus, the inverters are used and the parameters of the resonators are determined as explained in [26]. Microwave circuit of this filter is shown in **Figure 12a**.
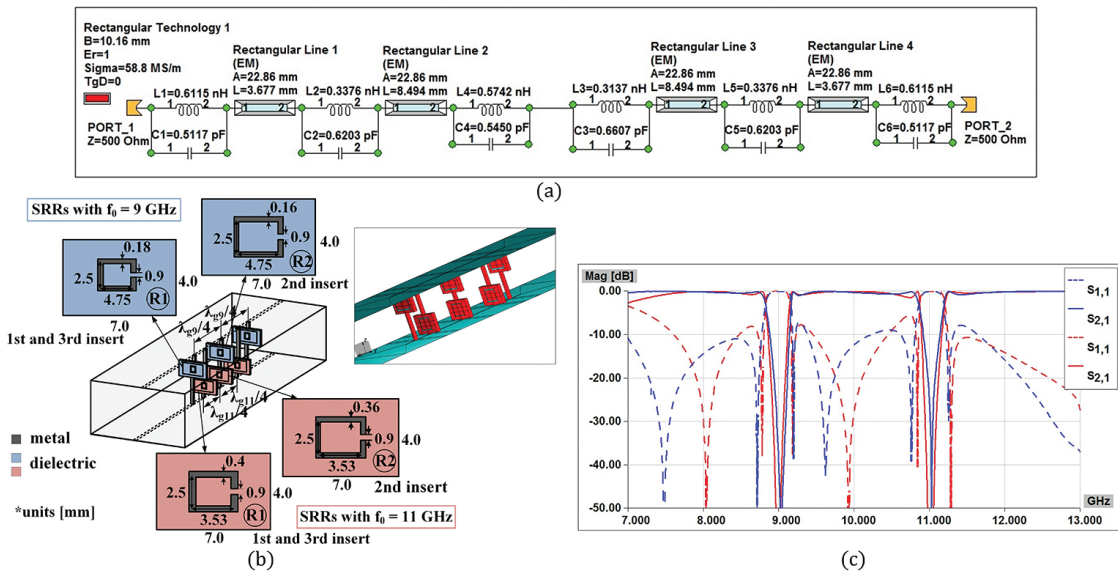
Figure 12. Third-order dual-band bandstop filter: (a) microwave circuit, (b) 3D model, (c) comparison of amplitude responses (blue—3D EM model, red—microwave circuit).

The 3D model of the filter is shown in **Figure 12b**. The inserts are optimally positioned so the inverters can be properly realized between the corresponding resonators, as explained in details in [35]. Comparison of the amplitude responses of the microwave circuit and 3D EM model is given in **Figure 12c**, showing good matching of the obtained results and confirming the proposed filter design.

The experimental measurements for the filter using the presented inserts cannot be easily performed without finding a way to have stable inserts in the waveguide. Therefore, a structure for precise positioning, in a form of ladder fixtures, is introduced in [42]. Since we use dielectric inserts, the fixtures are also designed using dielectric substrate although they can be made as multi-layer planar structures. These fixtures are attached to the top and bottom waveguide walls, and the inserts are attached to them. As shown in [42], the use of the fixtures does not degrade the filter response, so they can be used for precise positioning of inserts in the measurement procedure.

8. Conclusion

Starting from the microwave filter design principles, a method for the advanced waveguide filter design has been developed. It is based on the use of printed-circuit discontinuities as resonating elements. Relatively simple resonators, such as SRRs, CSRRs and QWRs, have been used for the printed-circuit insert design. In spite of their simple forms, these types of resonators provide a lot of possibilities to tune the amplitude response. Since multiple resonant frequencies can be obtained using single insert, these inserts can be employed for the multiband filter design. Therefore, various implementations of novel waveguide filters have been made using H-plane or E-plane inserts. For bandpass filters, metal or multilayer planar inserts with CSRRs have been used. Also, a compact filter solution has been proposed. Furthermore, bandstop filters have been designed using planar inserts with SRRs and QWRs. Besides 3D EM simulations and microwave circuits of the considered filters, prototypes have been fabricated so the amplitude responses can be measured. Also, structures for precise positioning of inserts, for bandpass and bandstop filters, have been designed and fabricated, since they are necessary to smoothly perform the measurements on the laboratory prototypes. The obtained experimental results have shown good agreement with the simulated ones, thus confirming the application of the proposed method for the advanced waveguide filter design.

Although considered waveguide filters are designed for radar and satellite systems, it is expected that the same design guidelines can be applied to the filters operating in other frequency bands by using the proper waveguide and scaling dimensions of the resonating components. Also, it can be further upgraded to keep up with the continuous technological development (e.g., tunable filter design). The most important advantage of the proposed method is a relatively simple design and implementation of structures which can be used in modern communication systems.

Acknowledgements

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References

[1]   Lutovac MD, Tošić DV, Evans BV. Filter Design for Signal Processing using MATLAB and Mathematica. Upper Saddle River, NJ: Prentice Hall; 2001 (Translated in Chinese. Beijing, P. R. China: Publishing House of Electronics Industry, PHEI; 2004).

[2]   Cameron RJ, Kudsia CM, Mansour RR. Microwave Filters for Communication Systems: Fundamentals, Design, and Applications. New Jersey: John Wiley & Sons; 2007.

[3]   Hunter I. Theory and Design of Microwave Filters. London: The Institution of Engineering and Technology; 2006.

[4]   Marcuvitz N. Waveguide Handbook. Stevenage, UK: Peter Peregrinus Ltd., on behalf of the Institution of Electrical Engineers; 1986.

[5]   Budimir D, Glubokov O, Potrebic M. Waveguide filters using T-shaped resonators. Electronics Letters. 2011;27(1):38–40. doi:10.1049/el.2010.2958

[6]   Jitha B, Nimisha CS, Aanandan CK, Mohanan P, Vasudevan K. SRR loaded waveguide band rejection filter with adjustable bandwidth. Microwave and Optical Technology Letters. 2006;48(7):1427–1429. doi:10.1002/mop.21641

[7]   Kehn MNM, Quevedo-Teruel O, Rajo-Iglesias E. Split-ring resonator loaded waveguides with multiple stopbands. Electronics Letters. 2008;44(12):714–716. doi:10.1049/el:20081108

[8]   Ortiz N, Baena JD, Beruete M, Falcone F, Laso MAG, Lopetegi T, Marques R, Martin F, Garcia-Garcia J, Sorolla M. Complementary split-ring resonator for compact waveguide filter design. Microwave and Optical Technology Letters. 2005;46(1):88–92. doi:10.1002/mop.20909

[9]   Bahrami H, Hakkak M, Pirhadi A. Analysis and design of highly compact bandpass waveguide filter utilizing complementary split ring resonators (CSRR). Progress in Electromagnetics Research. 2008;80:107–122. doi:10.2528/PIER07111203

[10]   Fallahzadeh S, Bahrami H, Tayarani M. A novel dual-band bandstop waveguide filter using split ring resonators. Progress in Electromagnetics Research. 2009;12:133–139. doi:10.2528/PIERL09103103

[11]   Fallahzadeh S, Bahrami H, Tayarani M. Very compact bandstop waveguide filters using split-ring resonators and perturbed quarter-wave transformers. Electromagnetics. 2010;30:482–490. doi:10.1080/02726343.2010.483942

[12]   Miljanović D, Potrebić M, Tošić DV. Design of microwave multibandpass filters with quasilumped resonators. Mathematical Problems in Engineering. 2015;2015(Article ID 647302):1–14. doi:10.1155/2015/647302

[13]   Miljanović D, Potrebić M, Tošić DV, Stamenković Z. Design of miniaturized bandpass filters using quasi-lumped multilayer resonators. Journal of Circuits, Systems and Computers. 2014;23(6):1450083. doi:10.1142/S0218126614500832

[14] Potrebić M, Tošić DV. A novel design of a compact multilayer resonator using double-sided microstrip. Optoelectronics and Advanced Materials-Rapid Communications. 2012;6(3–4):441–445.   [online]   http://oam-rc.inoe.ro/index.php?option=   maga-zine&op=view&idu=1851&catid=71

[15] Potrebić M, Tošić DV. Selective bandpass filter with concentrated impulse response. Microwave and Optical Technology Letters. 2008;50(11):2772–2777. doi:10.1002/mop.23785

[16] Pozar DM. Microwave Engineering. New York: John Wiley; 2012.

[17] Collin RE. Foundations for Microwave Engineering. New York: McGraw-Hill; 1992 (Reprinted by John Wiley—IEEE Press; 2001).

[18] Bonache J, Martin F, Falcone F, Baena JD, Lopetegi T, Garcia-Garcia J, Laso MAG, Gil I, Marcotegui A, Marques R, Sorolla M. Application of complementary split-ring resonators to the design of compact narrow band-pass structures in microstrip technology. Microwave and Optical Technology Letters. 2005;46(5):508–512. doi: 10.1002/mop.21031

[19] Baena JD, Bonache J, Martin F, Marques Sillero R, Falcone F, Lopetegi T, Laso MAG, Garcia-Garcia J, Gil I, Portillo MF, Sorolla M. Equivalent-circuit models for split-ring resonators and complementary split-ring resonators coupled to planar transmission lines. IEEE Transactions on Microwave Theory and Techniques. 2005;53(4):1451–1461. doi:10.1109/TMTT.2005.845211

[20] Bonache J, Gil I, Garcia-Garcia J, Martin F. Complementary split rings resonators (CSRRs): towards the miniaturization of microwave device design. Journal of Computational Electronics. 2006;5(2–3):193–197. doi:10.1007/s10825-006-8843-0

[21] Kim SI, Jang MY, Kee CS, Park I, Lim H. Characteristics of microwave filters based on microstrip photonic bandgap ring structures. Current Applied Physics. 2005;5(6):619–624. doi:10.1016/j.cap.2004.08.008

[22] Fan JW, Liang CH, Dai XW. Design of cross-coupled dual-band filter with equal-length split-ring resonators. Progress in Electromagnetics Research. 2007;75:285–293. doi: 10.2528/PIER07060904

[23] Li D, Xie YJ, Wang P, Yang R. Applications of split-ring resonances on multi-band frequency selective surfaces. Journal of Electromagnetic Waves and Applications. 2007;21(11):1551–1563. doi:10.1163/156939307782000271

[24] Wu GL, Mu W, Dai XW, Jiao YC. Design of novel dual-band bandpass filter with microstrip meander-loop resonator and CSRR DGS. Progress in Electromagnetics Research. 2008;78:17–24. doi:10.2528/PIER07090301

[25] Matthaei GL, Young L, Jones EMT. Microwave Filters, Impedance Matching Networks, and Coupling Structures. New York: McGraw-Hill; 1964 (Reprinted by Norwood, MA: Artech House; 1980).

[26] Hong JS. Microstrip Filters for RF/Microwave Applications. New Jersey: John Wiley & Sons; 2011.

[27] Jarry P, Beneat J. Advanced Design Techniques and Realizations of Microwave and RF Filters. New Jersey: John Wiley & Sons; 2008.

[28] Stefanovski SLJ. Microwave waveguide filters using printed-circuit discontinuities [Ph.D. dissertation, advisor: prof. dr Milka Potrebić]. Belgrade: School of Electrical Engineering, University of Belgrade; 2015.

[29] Stefanovski Pajović S, Potrebić M, Tošić D. Microwave bandpass and bandstop waveguide filters using printed-circuit discontinuities. In: Proceedings of the 23rd Telecommunications Forum (TELFOR 2015); N/A, 24–26 November 2015; Belgrade, Serbia. pp.520–527.

[30] Kolundžija BM, Djordjević AR. Electromagnetic Modeling of Composite Metallic and Dielectric Structures. Norwood, MA: Artech House; 2002.

[31] Potrebić MM, Tošić DV, Cvetković ZŽ, Radosavljević N. WIPL-D modeling and results for waveguide filters with printed-circuit inserts. In: Proceedings of the 28th International Conference on Microelectronics N/A, (MIEL 2012); 13–16 May 2012; Niš, Serbia. pp. 309–312.

[32] Stefanovski S, Potrebić M, Tošić D. Design and analysis of bandpass waveguide filters using novel complementary split ring resonators. In: Proceedings of the 11th International Conference on Telecommunications in Modern Satellite, Cable and Broadcasting Services (TELSIKS 2013); N/A, 16–19 October 2013; Niš, Serbia. pp. 257–260.

[33] Stefanovski S, Potrebić M, Tošić D, Cvetković Z. Design and analysis of bandstop waveguide filters using split ring resonators. In: Proceedings of the 11th International Conference on Applied Electromagnetics (PES 2013); N/A, 1–4 September 2013; Niš, Serbia. pp.135–136.

[34] Stefanovski S, Potrebić M, Tošić D. Novel realization of bandstop waveguide filters. Technics. N/A., 2013; pp.69–76 (special edition). [online] http://www.sits.org.rs/include/data/ docs0485.pdf

[35] Stefanovski S, Potrebić M, Tošić D. A novel design of dual-band bandstop waveguide filter using split ring resonators. Journal of Optoelectronics and Advanced Materials. 2014;16(3–4):486–493. [online] http://joam.inoe.ro/index.php?option=magazine&op=view&idu=3461&catid=83.

[36] Stefanovski S, Potrebić M, Tošić D, Cvetković Z. Bandstop waveguide filters with two or three rejection bands. In: Proceedings of the 29th Conference on Microelectronics (MIEL 2014); N/A, 12–15 May 2014; Belgrade, Serbia. pp. 435–438.

[37] Stefanovski S, Potrebić M, Tošić D. A novel design of E-plane bandstop waveguide filter using quarter-wave resonators. Optoelectronics and Advanced Materials—Rapid

Communications. 2015;9(1–2):87–93. [online] http://oam-rc.inoe.ro/index.php? option=magazine&op=view&idu=2487&catid=88

[38] Villarroya RL. E-plane Parallel Coupled Resonators for Waveguide Bandpass Filter Applications [Ph.D. dissertation]. Edinburgh, Scotland, UK: Heriot-Watt University; 2012.

[39] Stefanovski S, Mirković Đ, Potrebić M, Tošić D. Novel design of H-plane bandpass waveguide filters using complementary split ring resonators. In: Proceedings of Progress in Electromagnetics Research Symposium (PIERS 2014); N/A, 25–28 August 2014; Guangzhou, China. pp. 1963–1968.

[40] Stefanovski S, Potrebić M, Tošić D, Stamenković Z. A novel compact dual-band bandpass waveguide filter. In: Proceedings of IEEE 18th International Symposium on Design and Diagnostics of Electronic Circuits and Systems (DDECS 2015); N/A, April 22–24 2015; Belgrade, Serbia, p. 51–56.

[41] Stefanovski S, Potrebić M, Tošić D, Stamenković Z. Compact dual-band bandpass waveguide filter with H-plane inserts. Journal of Circuits, Systems, and Computers. 2016;25(3):1640015 (18 pages). doi:10.1142/S0218126616400156

[42] Stefanovski S, Potrebić M, Tošić D. Structure for precise positioning of inserts in waveguide filters. In: Proceedings of the 21st Telecommunications Forum (TELFOR 2013); N/A, 26–28 November 2013; Belgrade, Serbia, pp. 689–692.