Chapter

Analysis and Design of Miniaturized Substrate Integrated Waveguide CSRR Bandpass Filters for Wireless Communication

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Abstract

Microwave planar bandpass filters are indispensable in wireless communication systems in most applications. With miniaturization and limited spectrum, there is a great need for a compact, selective bandpass filter with a wide stopband performance. Substrate integrated waveguide (SIW) has become a potential technology for designing and developing microwave and millimeter-wave components, circuits, and systems. This chapter presents novel, compact metamaterial-based bandpass filters with improved stopbands. Several filters’ design methodology and performance are evaluated using broadside-coupled complementary split-ring resonators (BC-CSRR) and edge-coupled complementary split-ring resonators (EC-CSRR) techniques. A comprehensive method to evaluate negative permittivity and permeability for designing the proposed metamaterial structure is also described. These filters have not only compact size but also a wider upper stopband resulting from bandstop resonator characteristics.

Keywords: substrate integrated waveguide, miniaturization, BPF, EC-CSRR, BC-CSRR

1. Introduction

Filters play a vital role in numerous microwave applications. A microwave bandpass filter (BPF), in general, is a class of filter that is utilized to operate on the frequency response within the range of frequencies lying between 300 MHz and 300 GHz and allowing the best signal transmission at desired frequencies (passband), while eliminating signals at redundant frequencies (stopband) [1]. Among various techniques to design a bandpass filter, substrate integrated waveguides (SIWs) [2] are becoming more popular recently. SIW is a planar structure that is fabricated by using two periodic rows of conducting cylindrical vias implanted in a dielectric substrate, as shown in Figure 1. Hence, it acts as a bridge between planar and nonplanar technology.
To design efficient and well-performing wireless systems, there is a great need to design compact, lightweight microwave components. Over the past few years, various SIW miniaturization techniques have been proposed by researchers. Recently, [3] has reviewed the recent trends and various miniaturization techniques of SIW. Recently, folded SIW (FSIW) technique (C & T type FSIW) has been proposed by [4, 5]. Miniaturization was achieved using half mode SIW and Hilbert fractal for 5G applications [6]. Further, [7] proposed a ridge SIW to achieve miniaturization and suppress the harmonics.

From the design Equations [8] for a substrate integrated waveguide (SIW), d as the diameter of the vias and p as distance between the vias known as pitch, the equivalent width of dielectric-filled rectangular waveguide,

$$W_{EQ} = \frac{c}{2f_c\sqrt{\varepsilon_r}}$$  \hspace{1cm} (1)

Width of SIW,

$$W_{SIW} = W_{EQ} + \frac{d^2}{0.95p}$$  \hspace{1cm} (2)

Also, for choosing the value of $p$ and $d$, the following inequalities should be satisfied.

$$p < 4d \text{ and } p < \frac{\lambda_0}{2\sqrt{\varepsilon_r}}$$  \hspace{1cm} (3)

2. Metamaterial

A metamaterial is a word derived from the Greek word—it is a combination of the words “meta” and “material,” in which “meta” means something beyond normal, altered, changed, or something advanced. It is an artificial material designed to obtain the physical properties that do not exist in natural materials. A metamaterial [9] is an artificially engineered material with desirable properties not found in nature. A metamaterial affects electromagnetic waves by having structural features smaller than the wavelength of the medium of electromagnetic interaction. Metamaterials rely mainly on their physical structure to manipulate the electromagnetic waves to exhibit superior characteristics.
In 1999, John Pendry was the first to identify a practical way to make a left-handed metamaterial. Pendry’s theoretical idea was that metallic wires aligned along the direction of a wave could provide negative permittivity ($\varepsilon < 0$), and a split ring with its axis placed along the direction of wave propagation could do so could provide negative permeability. In 2000, Smith et al. reported the experimental demonstration of functioning electromagnetic metamaterials by stacking, periodically, split-ring resonators and thin wire structures as shown in Figure 2.

### 2.1 Metamaterials’ characteristics

Metamaterials with negative RI have numerous interesting properties. Several physical phenomena are reversed in LH media and at the intersection between LH and RH media due to the opposite sign of phase and group velocities. Some of the effects are:

- Reversal of Snell’s law
- Reversal of Doppler effect
- Reversal of Vavilov-Cherenkov radiation
- Lensing effect (convex lenses produce diverging rays, which is opposite to RH lenses)
- The time-averaged Poynting vector ($S$) is antiparallel to phase velocity

### 2.2 Metamaterial’s classification based on their properties

Russian scientist Veselago first proposed the metamaterial classification by considering the permittivity, $\varepsilon$, and the permeability, $\mu$ of a homogeneous material.
The relationship between the refractive index and the constituent parameters $\varepsilon$ and $\mu$ is given by the formula:

$$n = \pm \sqrt{\varepsilon_r \mu_r}$$  \hspace{1cm} (4)

where $\varepsilon_r$ and $\mu_r$ are the relative permittivity and permeability of the material. From Eq. (4), sign $\pm$ of $n$ can get 1 in the four cases, which depends on the pairs of the sign of $\varepsilon_r$ and $\mu_r$. The electromagnetic metamaterials are classified based on each case of the pair sign $\varepsilon$ and $\mu$; they are shown in Figure 3.

In quadrant I, both parameters $\varepsilon$ and $\mu$ are positive and are called double positive (DPS) or right-handed medium (RHM). In quadrant II, the parameters are $\varepsilon < 0$—negative, and $\mu > 0$—positive, and such material is called epsilon negative (ENG) medium and is represented by plasma. In quadrant III, parameters $\varepsilon < 0$—negative, and $\mu < 0$—negative, this region is called double-negative (DNG) or left-handed medium (LHM), and such material could not be found in nature. The quadrant IV $\varepsilon > 0$—positive, and $\mu < 0$—negative, such material is called $\mu$—negative (MNG), represented by ferrite materials.

2.3 Types of metamaterial

A split-ring resonator (SRR) is a type of metamaterial, which is artificially created. SRR cell is made up of a pair of enclosed loops of nonmagnetic metals that split at
opposite ends, as shown in Figure 4. When these materials are exposed to the magnetic field of electromagnetic waves, they give strong magnetic coupling unavailable in conventional materials. When SRRs are arranged periodically (array), they provides negative permeability.

The above structure of SRR is known as edge-coupled split-ring resonator (EC-SRR) structure, which comprises concentric metal split rings printed on the same side of the dielectric substrate. EC SRR benefits of strong magnetic polarizability near resonance and easy fabrication. However, it has certain drawbacks: (i) Its electric size cannot be reduced below one-tenth of wavelength; (ii) it suffers from cross-polarizability/ bianisotropic effect. Another type of SRR overcomes these limitations, called broadside-coupled SRR (BC-SRR) [10]. In the BC-SRR configuration, the rings are etched on both faces of the substrate, as shown in Figure 5a. Similar to EC-SRR, charges formed in the lower half of the BC-SRR are the replica of charges formed in the upper half, as shown in Figure 5b. Though this formation of charge does not create an electric dipole, BC SRR is non-bianisotropic. Since both rings are of identical dimension and keep inverse symmetry, for this reason, cross-polarizability tensor vanishes.

The application of the Babinet principle leads to the origin of its counterpart known as a complementary split-ring resonator (CSRR) in which the rings are
engraved on the conductive surface, and its magnetic and electric characteristics are changed when compared with SRR.

3. SIW loaded with basic EC-CSRR structure

A SIW bandpass filter based on edge-coupled CSRRs was proposed for the first time in 2007 by [11]. The SIW filter consisted of the tapered transition line with the CSRR. As SIW possesses high-pass characteristic, whereas a CSSR manifests band-stop characteristic, therefore by integrating CSRR with SIW, a bandpass SIW filter is designed. Figure 6 depicts the structure of SIW with CSSR etched in the top side of the substrate.

3.1 Equivalent circuit model

Figure 7 depicts the equivalent lumped equivalent circuit for Figure 6. CSRRs etched in the center are excited by the electric field induced by the SIW. Therefore, this coupling can be labeled by connecting the SIW capacitance to the CSRR. In these models, L is the inductance of SIW vias, and C is the coupling capacitance between the CSRR and SIW. The resonator is represented by a parallel LC tank, where Lc and Cc represent the reactive elements, and R accounts for losses.

Figure 6.
(a) Top and (b) bottom view of basic unit cell [11] [reproduced courtesy of the electromagnetics academy].

Figure 7.
The equivalent circuit model.
Figure 8a shows the dimensional geometry of the proposed SIW-CSRRs bandpass filter [11], and Figure 8b shows the photograph of the fabricated design. The substrate used in the filter is RT/Duroid 5880, with a permittivity of 2.2 and a height of 0.254 mm.

Figure 9 compares the simulated and measured results of the filter. The measured insertion and return losses are about 2.16 dB and 11.6 dB, respectively. The filter shows a wide bandwidth ranging from 6.2 to 8.6 GHz (FBW of 32.4%).

4. Study on effect of orientation of CSRR ring on frequency response

The effect of changing the orientations of the CSRR ring was exhaustively studied by [12], which was verified by simulations and experiments that modify CSRR’s orientations, different passband characteristics can be obtained. The orientation was specified with respect to the direction of the outer ring’s split, as shown in Figure 10. Hence, they are aligned face to face, back to back, and side by side. The side-by-side type has also been divided into two cases with the CSRRs reversely or equally oriented.
After simulation of various orientations, it was found that by altering the configuration of the CSRRs in a particular position (face-to-face orientation), the propagation of TE10 mode can be suppressed, resulting in enhanced selectivity and stopband rejection of the filter. The waveguide width was chosen as \( w = 12.3 \text{ mm} \) to keep the cutoff frequency of the initial SIW at about 8.7 GHz. The Rogers substrate RT/Duroid 5880 with a thickness of 0.508 mm and a relative permittivity of 2.2 is used in the design. The metalized vias have a diameter of 0.8 mm and a center-to-center spacing of 1.48 mm.

After the simulation of various configurations, it was found that the unit cells with face-to-face and back-to-back oriented CSRR exhibit a similar kind of passband with one transmission zero and one pole located above the passband. Nonetheless, for the second case, the transmission zero is close to the pole leading to a steep upper side transition but with large insertion loss due to the weak coupling. For the third case, two rings are arranged side by side in opposite directions, and two transmission poles with two transmission zeros in the upper band are achieved. The propagation is quite weak for the fourth case due to weak magnetic coupling.

Eventually, a two-stage filter using the unit cell aligned face to face is simulated and fabricated using Rogers RT/Duroid 5880. A distance of 8.8 mm separates the two cells. The proposed bandpass filter achieves one transmission zeros at 6.4 GHz in the upper band, resulting in high selectivity and a wide upper stopband. The two-pole filter has a measured center frequency of 5.0 GHz and a 3-dB bandwidth of 0.33 GHz (3.2% FBW).

5. Bandpass filter with diamond-shaped edge-coupled CSRR (EC-CSRR)

Recently, a novel bandpass filter using diamond-shaped edge-coupled CSRR was proposed [13]. This section discusses the design methodology of single-stage and two-stage bandpass filters with diamond-shaped EC-CSRR structures.

5.1 Single-stage BPF with diamond-shaped CSRR

The physical construction of CSRR is shown in Figure 11, where the upper orange part is the conducting layer, and the light gray part is the substrate. The CSRR structure consists of two diamond-shaped split resonant rings with their openings opposite (face to face) to each other for tight coupling between them. As CSRRs are integrated
with SIW, a passband with an evanescent resonant mode lower than the SIW’s cutoff frequency is created, miniaturizing the size of the conventional SIW [13]. Figure 11 shows the dimensional view of a single-stage SIW filter loaded with diamond-shaped CSRR. The optimized dimensions of filter are: length of single-stage SIW $L_{SIW} = 10$ mm, width of SIW $W_{SIW} = 8.5$ mm, the inner radius of ring $R1 = 1.0$ mm, the outer radius of ring $R2 = 1.6$ mm, the thickness of ring $T = 0.25$ mm, the gap between open ends of outer ring $G = 0.40$ mm, the perpendicular distance between outer rings $S = 1.25$ mm. Figure 12 shows the frequency response of single-stage CSRR incorporating SIW filter. The figure shows that in a single-stage SIW filter, one passband is formed with a center frequency of 8.75 GHz, below the waveguide cutoff frequency causing miniaturization by approximately 33%. The passband has 3-dB bandwidth of 0.42 GHz with an in-band insertion loss of 0.62 dB. The maximum value of return loss is $-24.4$ dB. Also, the stopband created has a high rejection level at the upper stopband.
5.2 Two-stage BPF with diamond-shaped CSRR

The two-stage filter is proposed to improve the passband and stopband performance of the filter, as shown in Figure 13. The length of the two-stage SIW filter is taken as $L_{SIW} = 18$ mm with horizontal distance between centers of rings, $L = 8$ mm. Other dimensions remain the same as in the single-stage SIW bandpass filter. Hence, the total filter size of the two-stage is $1.2\lambda_0 \times 0.28\lambda_0$, where $\lambda_0$ is the free space wavelength of the center frequency of passband. Figure 14a and b show the current distribution of the proposed filter in the passband and stopband, respectively.

Figure 15 shows the simulated frequency response of two-stage SIW BPF. The response clearly shows that one passband is formed with two poles and transmission zero. The passband has a center frequency of 8.86 GHz with 3-dB bandwidth of 0.74 GHz and an in-band insertion loss of 0.48 dB. The maximum return loss is $-29.4$ dB. Further, the stopband rejection is more than 60 dB, which is relatively better than a single-stage filter. In the second stage of transmission, zero is in proximity to poles leading to a high roll-off rate of 72.5 dB/GHz and 40.5 dB/GHz at the upper and lower edge, respectively.

6. Novel substrate integrated waveguide bandpass filter with broadside-coupled complementary split ring resonators

A novel SIW BPF using broadside-coupled complementary split-ring resonator (BC-CSRR) pairs was implemented for the first time by [14]. Figure 16 (left) shows

![Figure 13. Schematics of two-stage SIW BPF.](image)

![Figure 14. (a) Current distribution in the passband. (b) Current distribution in the stopband.](image)
the structure of the BC-SRR (broadside-coupled split-ring resonator). It can be derived from EC-SRR by substituting one of the rings with another ring situated precisely at the opposite side of the substrate. From the duality principle, the negative image of the BC-SRR is termed as the broadside-coupled complementary split-ring resonator (BC-CSRR), as shown in Figure 16 (right).

6.1 The SIW BC-CSRR pair

Figure 17 depicts the layout of the proposed SIW BC-CSRR. It is evident that two BC-CSRRs are aligned side by side with opposite orientations to each other. A microstrip feed line is used to excite the SIW cavity. For the selected dielectric substrate with $\varepsilon_r = 2.65$ and waveguide cutoff frequency of 8.15 GHz, the width of the SIW ($w$) is calculated to be 12.5 mm. Figure 18 shows the simulated transmission response for the SIW integrated with the unit cell. It is evident from the response that it creates a passband with a center frequency of 5.6 GHz, which is below waveguide cutoff frequency.

6.2 Two-stage BPF with BC-CSRR unit cell

Figure 19 depicts the proposed two-stage BC-CSRR BPF with separation between rings ($l_d = 7$ mm).
Figure 20 shows the photograph of the fabricated filter using a substrate with $\varepsilon_r = 2.65$ and a thickness of 1 mm. Figure 21 compares the simulated and measured frequency response of the BPF. The measured center frequency and 3-dB bandwidths are 5.75 GHz and 0.32 GHz, respectively. The measured in-band return loss is below 12 dB. The dimension of the filter is 20 mm x 13 mm ($0.38 \times 0.25 \lambda_{o2}$).
7. Miniaturized and selective SIW bandpass filter with S-shaped broadside-coupled complementary split-ring resonators (BC-CSRR)

This work [15] proposes the design of a substrate integrated waveguide (SIW) bandpass filter (BPF) incorporated with a novel broadside-coupled complementary split-ring resonator (BC-CSRR). The complementary double S shape as metamaterial is carved on the top and broad bottom walls of SIW with orientation 180° to each other. The proposed filter is designed for X band using substrate alumina with a relative permittivity of 9.8 and height of 0.508 mm. Further, the width of the SIW, $W_{SIW}$ is set to 5.4 mm to keep the nominal cutoff frequency of the waveguide to 10 GHz using SIW design equations.

7.1 Analysis and design of metamaterial

For designing the proposed S-shaped metamaterial, a double S-shaped structure was placed one above the another in an antisymmetrical manner over a dielectric layer forming a shape of 8 [16]. S on both sides of the dielectric forms metamaterial that simultaneously provides negative permeability and permittivity. The side length of the S shape is kept equal to $\lambda g/4$ ($A = 2.25$ mm), and thickness $T$ is kept equal to 0.35 mm, as shown in Figure 22.
Figure 23 depicts the setup to get S parameters of complementary S-shaped metamaterial using HFSS. For this, two-layered dielectric substrates (alumina) having relative permittivity 9.8 of thickness 0.508 mm are stacked over each other. The S-shaped structure is placed on the opposite side of the top dielectric substrate one above the other (in a complementary manner) to form Figure 8. A 50 Ω microstrip line is provided at the bottom of the lower substrate.

In HFSS, first, simulate the metamaterial structure by providing the solution frequency. Then get S-parameters (S11, S21) in tabular form as follows:

1. Result - > Create Modal Simulation Data Report - > Data Table.
2. Create a data table for S(1,1) containing magnitude and angle in rad (phase).
3. Similarly, create a data table for S(2,1). These files have extension .csv (comma-separated values).
4. Export these .csv files to the same folder where MATLAB code is kept. Now, call these files S(1,1).csv and S(2,1).csv in parameter extraction MATLAB code [17] in function referred as DATA_READ specifying the path locations of files.
Successful execution of MATLAB code [17] for the parameter extraction results led to permittivity and permeability, as shown in Figure 24. The graph indicates that the permeability and permittivity are negative simultaneously for the frequency range between 7.25 GHz and 9.15 GHz. It illustrates that the structure has metamaterial characteristics for the frequency range between 7.25 GHz and 9.15 GHz.

7.2 Design of single-stage SIW BC-CSRR bandpass filter

Figure 25 shows single-stage BC-CSRR BPF, which has a pair of identical “S”-shaped etched on the SIW top and broad bottom walls but at 180° to each other. A tapered microstrip feed line has been used for exciting the SIW. The design parameters are taken as: \( W_{SIW} = 5.4 \text{ mm} \), \( L_{SIW} = 4.2 \text{ mm} \), \( P = 1.6 \text{ mm} \), \( D = 0.8 \text{ mm} \), \( L_T = 4 \text{ mm} \), \( W_T = 2 \text{ mm} \), \( L_M = 2 \text{ mm} \), \( W_M = 0.50 \text{ mm} \), \( A = 2.25 \text{ mm} \), and \( T = 0.35 \text{ mm} \).

Figure 26 shows the equivalent circuit of the single-stage BC-CSRR BPF. The equivalent circuit of the S-shaped SRR structure is given by [18], in which S-SRR is modeled by a series L-C circuit in each half ring of the eight-shaped structure through a common capacitor. Since CSRR is complementary to the SRR structure, the

![Figure 24](image)
Graph of real values of \( \mu \) and \( \epsilon \).

![Figure 25](image)
Schematics of single-stage SIW BC-CSRR BPF.
Figure 26.
Equivalent circuit of BC-CSRR BPF.

Figure 27.
Frequency response ($S_{11}$) of an equivalent lumped circuit of single-stage BC-CSRR SIW filter.

Figure 28.
Frequency response of single-stage BC-CSRR SIW filter.
equivalent circuit of single unit BC-CSRR will be dual of S-SRR. The metallic vias of the SIW are modeled as $L_v$.

**Figure 27** shows the simulated result of the equivalent lumped circuit using ADS. **Figure 28** shows the frequency response of single-stage BC-CSRR incorporated SIW filter. The figure shows that by etching the S structure in SIW, a passband is obtained with a center frequency of 8.2 GHz and 3-dB bandwidth of 0.15 GHz. The maximum return loss is 21.55 dB, and insertion loss is 0.32 dB at the center frequency. It can be seen that the resonant frequency of the SIW BC-CSRR element is well below the cutoff frequency of the original SIW, causing its miniaturization.

### 7.3 Design of two-stage SIW BC-CSRR bandpass filter

In order to improve roll-off factor and order of filter, cascaded connection [19] of two identical BC-CSRR structures is used to form two-stage BPF. **Figure 29** shows the

![Figure 29. Schematics of two-stage SIW BC-CSRR BPF.](image)

**Figure 30.** Parametric analysis of return loss for varying side length “a.”

![Figure 30.](image)
structure of two-stage BC-CSRR BPF with design parameters taken as: $W_{SIW} = 5.4$ mm, $L_{SIW} = 4.2$ mm $P = 1.6$ mm, diameter of via $D = 0.8$ mm, $L_T = 4$ mm, $W_T = 2$ mm, $L_M = 2$ mm, $W_M = 0.50$ mm, $A = 2.25$ mm, $T = 0.35$ mm, and $L = 4.25$ mm.

The distance ($L$) between two BC-CSRRs has a vital influence on the performance of the proposed two-stage filter. **Figure 30** shows the parametric analysis of return loss with varying values of $L$ (for $L = 3.25, 3.75, 4.25, 4.75, 5.25$ mm). It is clear from **Figure 30** that the filter shows optimum performance for $L = 4.25$ mm. For other small or big values of $L$, its response becomes undesirable.

**Figure 31a** and **b** depicts the current distribution in passband and stopband, respectively. As seen from the current distribution, it is clear that when the filter is passing the signal, the center resonator is resonant and has a large current that couples the signal through to the output.

**Figure 32** shows the frequency response of two-stage BS-CSRR. From the response, it can be observed that a passband with 3-dB bandwidth of 0.385 GHz is obtained. The simulated insertion loss is 0.32 dB, and the simulated roll-off rate at the lower and upper edge of the passband is calculated to be 78.26 dB/GHz and 65.5 dB/GHz, respectively. The maximum return loss value is 24.85 dB at the center frequency of 8.4 GHz with a 3-dB bandwidth of 0.38 GHz.

**Figure 31.**
Current distribution in (a) passband and (b) stopband.

**Figure 32.**
Frequency response of single-stage BC-CSRR SIW filter.
7.4 Fabrication and results

The proposed filter is fabricated using substrate material alumina with a relative dielectric constant of 9.8, \( \tan \delta = 0.001 \), and thickness of 0.508 mm to validate the result. Figure 33a and b shows the photograph of the top and bottom layer of the assembled filter with overall dimensions as 10 mm (length excluding transition) \( \times 8.5 \) mm (width).

The scattering parameters of the fabricated filter are measured by a vector network analyzer Anritsu S 820E. A two-port SOLT (short- open- load and thru) calibration has been done to consider cable losses between the VNA and the DUT. The measured and HFSS simulated results are compared and depicted in Figure 34a. It can be seen that the measured passband of the filter is from 8.20 GHz to 8.74 GHz with 3-dB bandwidth of 0.54 GHz. The maximum return loss value is 17.2 dB with an insertion loss of 0.92 dB in almost the entire passband. It achieves good attenuation (>20 dB) in the upper stopband. The measured roll-off rate is 58.5 dB/GHz and 60.2 dB/GHz at the lower and upper edge of the passband, respectively. Figure 34b depicts the simulated and measured VSWR plot for the entire range.

8. Conclusions

The metamaterials can be applied to enhance bandwidth, create a compact structure or multifrequency bands, etc. In this chapter, various compact and selective CSRR integrated SIW bandpass filters have been analyzed, demonstrating their
performance. To apply metamaterials, the first step is to design their unit cells, creating special metamaterial properties at the desired frequency. The size of the unit cells is calculated, simulated, and optimized using the HFSS software. First, three edge-coupled CSRR (EC-CSRR) BPFs have been analyzed for the design and performance. Then two broadside-coupled CSRR (BC-CSRR) BPFs have been analyzed elaborately and evaluated for performance.

Acknowledgements

This work was carried out during the tenure of ‘The European Research Consortium for Informatics and Mathematics (ERCIM) Alain Bensoussan’ Fellowship’ programme.

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