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A Compact Ultra-Wideband Bandpass Filter with Sharp-Rejection Using Complementary Split Ring Resonators

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ABSTRACT

A compact and sharp-rejection ultra-wideband (UWB) microstrip bandpass filter (BPF) is developed using of left handed metamaterials realized by complementary split ring resonator (CSRR). Moreover, proposed structure consists of two doublets parallel coupling gaps at each side of a microstrip ring. This structure shows a significantly wider passband due to the introduction of a cross-coupling between the feed lines (input and output) which generate four pairs of attenuation poles in the passband. Also, using two CSRRs etched in the ground plane, and series gap inside the microstrip ring leads to the addition of two extra transmission poles at the lower and upper edges of the filter. Consequently, a compact six-pole ultra-wide bandpass filter is designed which exhibits extremely sharp rejection skirts around the target passband .The proposed filter has a passband covers 3.4 to 10.15 GHz and its measured 3 dB fractional bandwidth is about 100%. Furthermore, rejection level better than 20 dB in upper stopband is extended to around 14.7 GHz both in simulation and measurement. Experimental verification is provided and good agreement has been found between simulation and measurement. The total size of the proposed UWB filter is more compact compared with known similar filters.

KEYWORDS

Complementary split ring resonator (CSRR), Ultra-ideband (UWB), Bandpass Filter (BPF), Microstrip ring and doublets parallel coupling gaps.

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1. INTRODUCTION

A high performance ultra-wideband (UWB) bandpass filter (BPF) is desirable in UWB wireless communication systems. Since the federal communication commission (FCC) released the frequency band from 3.1 to 10.6 GHz for commercial communication applications in February 2002 [1], the UWB wireless communication technology has received much more attention from both communication literature and industry.

Recently, extensive works have been done to exploit the variety of UWB BPFs with different methods and structures as reported in papers [2–9, 11-23]. Wide bandwidth, multi-transmission poles, sharp lower and upper edges, compact size and good electrical performance are important characteristics in UWB filter design. The use of such filters in a UWB system results too many attractive benefits, such as transmission with high data rate and requirement of lower transmission power.

To achieve a wideband BPF, different configurations were introduced. For example, in [3] a microstrip stub-loaded dual-mode resonator doublet was proposed which this ultra-wide bandpass filter exhibit widen bandpass without sharp edges. In order to sharpen the edges of the filter, they proposed a three-order filter by cascading three stub-loaded resonator doublets at the cost of a larger filter size. Moreover, to achieve a wideband BPF, many ring resonator filters with various coupling approaches were reported [2-9]. In comparison with direct connecting configuration, the capacitive gap or coupled-line technique produce some interesting features and characteristics, including dc-rejection and highly attenuation of stop band [4-8]. For example, in [7] an ultra-wideband (UWB) BPF with a notched band, by utilizing asymmetric structure in interdigital-coupled feed lines is proposed. Also in [9], a ring resonator with the aid of embedded ring resonator is proposed that provides a wide bandwidth and a wide stopband performance. The wide stopband is reaped without cascading the core structure.

On the other hand, in the past few years, there has been a rising interest in the field of metamaterials which can also be used in realization of UWB filters. Although the electromagnetic properties of left handed metamaterial had been predicted by Veselago in the late sixties [10] such a media were not artificially fabricated until 2000 [10]. Among various implementations for metamaterial structure, the resonant-type approach which is consist of the split ring resonators (SRRs) and complementary split ring resonators (CSRRs) have been more used for the design of microwave filters. These metamaterial resonant elements are electrically small which exhibit an effective negative permittivity or permeability in a narrow band at the resonate frequencies.

In planar technology, one-dimensional left handed transmission lines with negative permittivity which is realized by etching the CSRRs on the back substrate side have been recently proposed [11-13]. It has been indicated that left-handed transmission lines consisting of a combination of SRRs with shunt-connected strips (or vias), or CSRRs with series gaps, exhibit an abrupt transition pole at the lower or upper edge of the passband.

In this paper, a compact UWB bandpass filter operating in the FCC's frequency range is proposed. When two doublets parallel coupling gaps in both input and output are arranged with a microstrip ring, it exhibits a significantly widened passband. Although the microstrip ring with two doublets parallel coupling gaps has an excellent performance over the passband, its attenuation slope in the stopband is quite slow [2].

In order to get sharp attenuations near the passband and increase the bandwidth simultaneously, we use left handed metamaterial which is implemented by CSRRs and series gap for adding two transmission poles at the lower and upper edges of the filter. As a result, the filter exhibits extremely sharp rejection skirts at the lower and upper edges and the bandwidth is also increased. The proposed UWB filter shows six transmission poles within its passband covering 3.4-10.15 GHz and sharp attenuations near the passband are realized. Furthermore, the UWB BPF achieves an upper stopband performance with more than 20 dB attenuation up to 15.2 GHz. The simulation results of the UWB filter is carried out using Agilent ADS simulator. The proposed UWB filter has compact size and the minimum strip width and gap width of 0.2 mm and 0.1 mm, respectively. So it is possible to fabricate the proposed filter at low cost. The measured frequency response of the designed filter shows good agreement with the theoretical prediction, and the FCC's indoor limit is well satisfied.

2. Complementary Split Ring Resonator (CSRR*)*

Metamaterial is an artificial effective homogeneous electromagnetic structure with negative values of ε and μ, simultaneously. As metamaterials are frequency-selective structures by nature, their application to the design of compact microwave filters seems to be straightforward. Probably the most outstanding property of metamaterial transmission lines is the controllability of the electrical characteristics. Owing to this control, it is possible to design components with superior performance compared to conventional implementations such as enhanced bandwidth devices, or microwave devices with small dimensions. It was shown that SRRs and CSRRs are useful components for the synthesis of narrowband and wide-bandpass filters [10]. The SRRs provide the negative effective permeability, μ, to the medium in a narrow band above their resonant frequency. The concept of complementary split ring resonators (CSRRs) which is introduced as an alternative for design of metamaterials based on resonant elements provides an effective negative permittivity, ε, rather than permeability [10]. By invoking the concepts of duality and Babinet principle [10], the CSRR can be derived from the SRR structure in a straightforward way. This element, which in planar technology can be defined as the negative image of the SRR, exhibits an electromagnetic behavior which is almost the dual of that of the SRR. Specifically, a negative effective permittivity can be expected for any CSRR-based medium, whereas a negative, μ, behavior arises in an equivalent SRR-based system. In view of the fact that this behavior occurs in a narrow band above SRRs or CSRRs resonance, and the period of the structure is electrically small, these metamaterial transmission lines are useful in filter applications where miniaturization and sharp rejection are pursued. The topology of the CSRR (dual of the SRR model) is shown in Figure 1. It is well known that, the complementary of a planar metallic structure is obtained by replacing the metal parts of the original structure with apertures, and the apertures with metal plates. Thus, the resonance frequency of the CSRR is obtained from:

$$\omega_0 = \frac{1}{\sqrt{L_C C_C}} \qquad (1)$$

Fig. 1. Topology of the CSRR.

The natural (although not exclusive) host transmission line for implementation of one-dimensional metamaterials using CSRRs is the microstrip configuration. Due to the negative effective permittivity in the vicinity of CSRR's resonance, signal is inhibited in a narrow band. In order to synthesize the left-handed medium, additional elements which provide required negative permeability must be introduced to the structure. It was shown that the negative effective permeability can be achieved by etching series capacitive gaps in the host line. It was shown in [10] that left-handed transmission lines consisting of a combination of SRRs with shunt-connected strips (or vias), or CSRRs with series gaps, exhibit an abrupt transition band at the lower or upper edges of the filter.

3. Design of Six-Pole UWB Bandpass Filter

A ring resonator is merely a transmission line formed in a closed loop [2]. In the proposed design, the rectangular microstrip ring resonator is placed between two doublets parallel coupling gaps (Figure 2). Using two doublets parallel coupling gaps and a microstrip ring, four pairs of resonant poles are produced. Adopting the methods reported in [2], we show that, two single parallel coupling gaps with ring resonator produce the transmission poles within the passband. The single parallel coupling gaps with rectangular ring resonator are a symmetrical structure with respect to the central dot-dashed line shown in Figure 2. Therefore, only half of the structure should be analyzed using the even-mode and odd-mode methods [9, 20]. The model can be divided into two sections from the symmetric plane, an open circuit for even mode and a short circuit for odd mode, as shown in Figures 3(a) and 3(b). The input and output transmission lines of the resonator have a characteristic impedance of Z_0, and the single parallel transmission-lines have an electrical length of θ_1 with characteristic impedances of Z_1. The square ring resonator has electrical lengths of θ_2 and θ_3 in its vertical and horizontal sides, respectively, with characteristic impedance of Z_2. Also, the series gap has electrical lengths of θ_4 and θ_5 with characteristic impedances of Z_4 and Z_5 which presented in Figures 3(a) and 3(b). In practice, the embedded symmetrical series gap within the rectangular ring would not affect the characteristics of the transmission poles unless a small shift of the poles within the passband [20]. Therefore, the parameters of (θ_4, Z_4) and (θ_5, Z_5), shown in Figures 3(a) and 3(b), can be ignored in even- and odd-mode analyses. So, even-mode input impedance can be derived as [21]:

$$Z_{ine} = Z_1 \frac{j\left\{Z_1 \tan\theta_1 - \frac{1}{2} Z_2 \cot\left(\left(\theta_2+\theta_3\right)/2\right)\right\}}{Z_1 + \frac{1}{2} Z_2 \cot\left(\left(\theta_2+\theta_3\right)/2\right)\tan\theta_1} \quad (2)$$

When $Z_{ine}=\infty$, even-mode resonance will occur, while the resonance condition is:

$$Z_1 + \frac{1}{2} Z_2 \cot\left(\left(\theta_2+\theta_3\right)/2\right)\tan\theta_1 = 0 \quad (3)$$

Similarly, the odd mode resonance input impedance can be calculated as [21]:

$$Z_{ino} = Z_1 \frac{j\left\{\frac{1}{2} Z_2 \tan\left(\left(\theta_2+\theta_3\right)/2\right) + Z_1 \tan\theta_1\right\}}{Z_1 - \frac{1}{2} Z_2 \tan\left(\left(\theta_2+\theta_3\right)/2\right)\tan\theta_1} \quad (4)$$

when $Z_{ino}=\infty$, odd-mode resonate has been occurred which the resonance condition is:

$$Z_1 - \frac{1}{2} Z_2 \tan\left(\left(\theta_2+\theta_3\right)/2\right)\tan\theta_1 = 0 \quad (5)$$

The S parameter of the two-port network can be calculated using the following equations [21]:

$$S_{11} = \frac{Z_{even} Z_{odd} - Z_0^2}{\left(Z_{even}+Z_0\right)\left(Z_{odd}+Z_0\right)} \quad (6)$$

$$S_{21} = \frac{Z_{even} Z_0 - Z_{odd} Z_0}{\left(Z_{even}+Z_0\right)\left(Z_{odd}+Z_0\right)} \quad (7)$$

Where Z_0 is the characteristic impedance of each port. The condition of transmission pole frequencies are obtained when $Z_{ino} = Z_{ine}$ [21]. The input impedances of the one-port transmission line circuits which are shown in Figure 3(a) and 3(b), have been calculated as Z_{ine} and Z_{ino}, based on which, the transmission and reflection coefficients of the two-port single parallel coupling gaps with ring resonator that in shown in Figure 2, are derived.

In Figure 5, the influence of the length l_1 of the feed lines on the frequency response of the doublet parallel coupling gaps with ring resonator is shown. Thus, the impedance matching bandwidth of this filter can be simply adjusted by changing the dimension of this gaps length. Three different lengths of l_1 are chosen, and they are 3.0mm, 4.0 mm, and 5.0 mm, respectively. It is seen that both the midband frequency and the bandwidth can be varied by changing the length of the feed lines. To increase the bandwidth and add the other two transmission poles in the passband, doublets parallel coupling gaps in each side of a microstrip ring are employed. Although placing two doublets parallel coupling gaps in each side of a microstrip ring has an excellent performance over the passband, its attenuation slope in the stopband is quite slow.

In order to sharpen the attenuations near the passband, the CSRRs and series gap are used. In the proposed structures, the gap is located between the rectangular microstrip ring, which is employed instead of the circular ring used in [2] and allows the series gap to be embedded in the microstrip ring with no change in size of the filter.

The external CSRR provide an attenuations pole at lower edge of the filter while the internal rings provide an attenuations pole at upper edge of the filter. Therefore, the CSRRs and the series gap lead to produce two other attenuation poles near the lower and upper edges.

For easy fabrication of the filter, all the gap widths between the strips in the filter are chosen as S=0.1mm, and the strip widths of the parallel coupling gaps are chosen as w_1=0.2mm. The layout (top and bottom layers) of proposed UWB filter is shown in Figure 4. Table I exhibits the dimensions of the proposed UWB filter shown in Figure 4, where all of them are in millimeters and the space between two parallel strips that form series gap in microstrip ring is 0.2 mm. The dimensions of the CSRRs, which loaded on the ground plane of the proposed UWB filter are summarized in Table II.

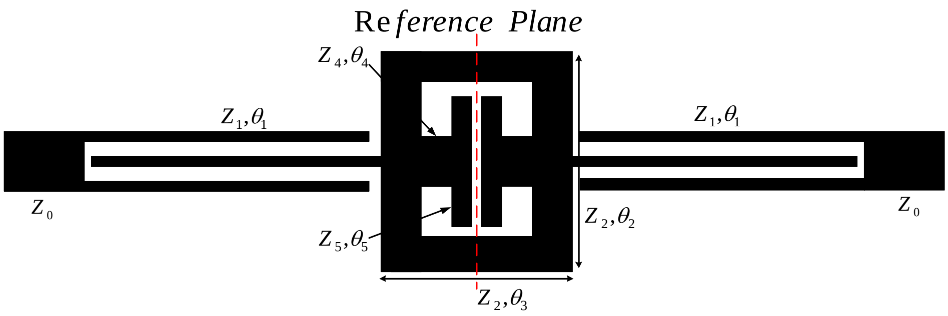

Fig. 2. Configurations of the proposed single parallel coupling gaps and ring resonator.

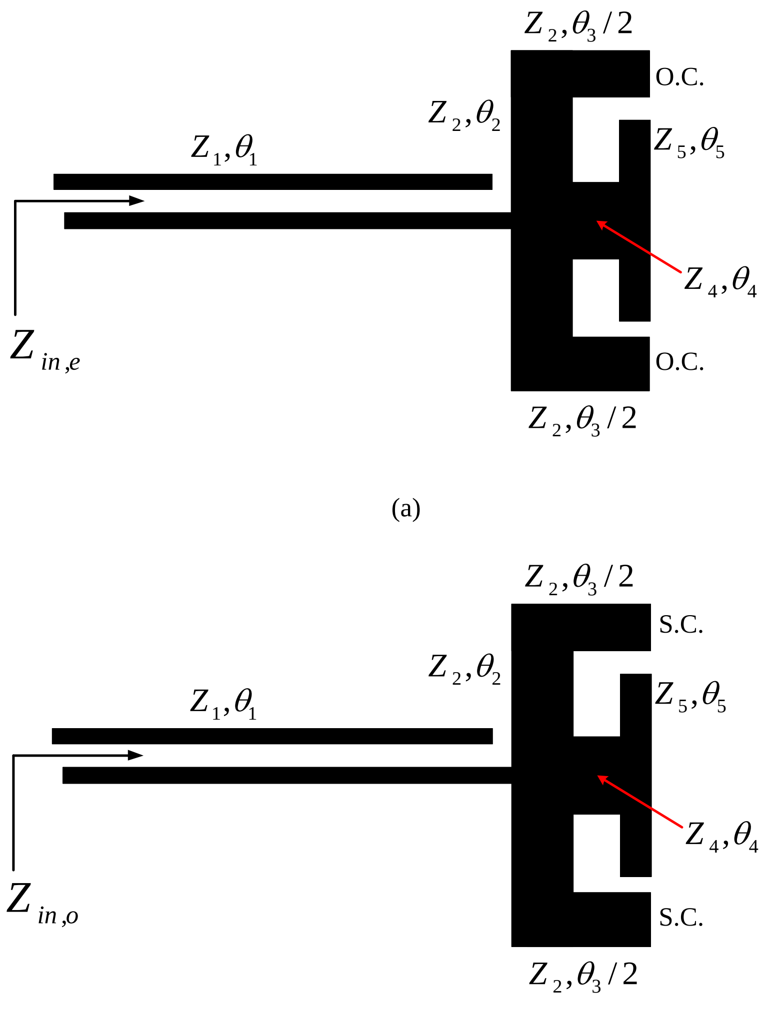

Fig. 3. Equivalent transmission line models of the single parallel coupling gaps shown in Figure 2 in the case of (a) odd-mode excitation, and (b) even mode excitation. Because of its symmetry, only half of the circuit is drawn in both (a) and (b)

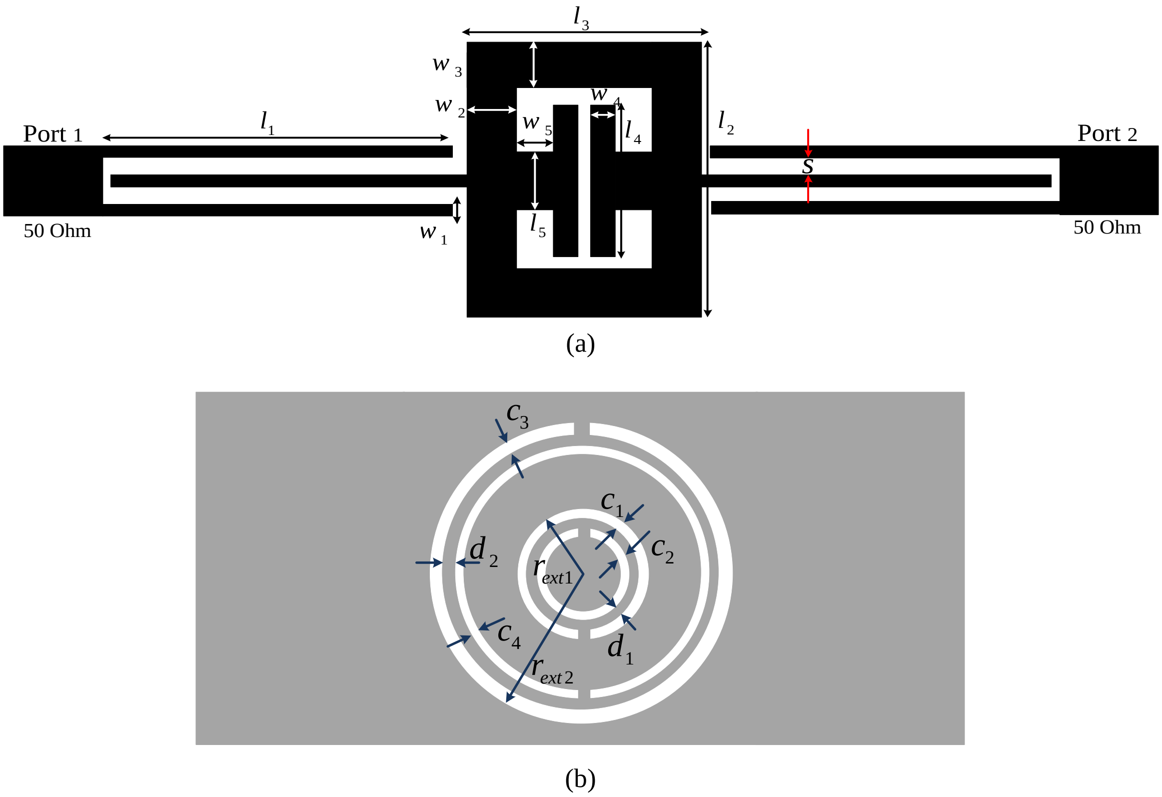

Fig.4 . Configurations of the proposed UWB filter. (a) Top and (b) bottom layers (Gray zone represents the metallization).

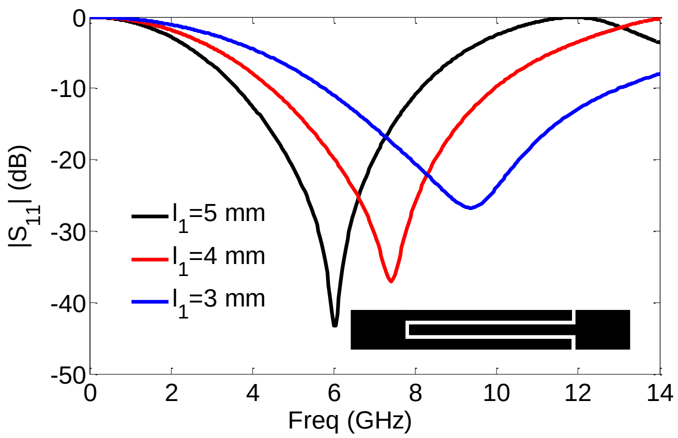

Fig. 5. Frequency response (|S11|) of the doublets parallel coupling gaps when the length l1 of the parallel coupling gaps is 3mm, 4mm and 5mm, respectively.

Table I.

Dimensions of the proposed UWB filter (units: mm)

l_1	4.5	w_3	0.6
w_1	0.2	l_4	2.6
l_2	4	w_4	0.3
w_2	0.6	l_5	1.2
l_3	2.8	w_5	0.4

Table II.

Dimensions of the CSRRs

smaller CSRR	larger CSRR
c_1 = 0.17 mm	c_3 = 0.22 mm
c_2= 0.17 mm	c_4 = 0.16 mm
d_1 = 0.11 mm	d_2 = 0.11 mm
r_{ext1} = 0.89 mm	r_{ext2} = 2.10 mm

Accordingly, the total size of the filter is less than 12 mm × 4.2 mm. The substrate is chosen to be Rogers RO3010 with the relative permittivity of 10.2 and the thickness of 1.27 mm.

4. Simulation and Measurement Results

A microstrip ultra-wideband bandpass filter operating at the frequency range of 3.4–10.15 GHz is designed and simulated. The frequency responses of the proposed UWB bandpass filter are simulated by Agilent ADS simulator whose results are presented in Figure 6. The proposed UWB bandpass filter exhibits the passband of 3.4–10.15 GHz, an insertion loss smaller than 1.68dB, and a return loss more than 16 dB in simulated results. The simulated and measured results show that the proposed BPF filter has a 3 dB fractional bandwidth of 100% from 3.4 to 10.15 GHz. Moreover, the FCC's indoor limit is satisfied quite well. Meanwhile, a wide upper-stopband with the attenuation higher than 20 dB in the range of 10.15 to 14.7 GHz is achieved. The photograph of the proposed UWB filter is shown in Figure 7, which demonstrates the quite small size of the filter. Again, for easy fabrication of the filter, all the gap widths between the strips in the filter are chosen as 0.1mm, and the strip widths of the resonators and feed lines are chosen as 0.2mm. Figure 8 illustrates the characteristics of the filter, measured by network analyzer (Rohde & Schwarz, zvk), which has a good agreement with simulation results. In the simulations, the metallic and dielectric loss have been taken into account by using the conductivity of copper $\sigma = 5.8\times10^7$ S/m and the loss tangent tan δ=0.002 of the substrate. Six transmission poles are observed within the passband covering approximately 3.4-10.15 GHz. Four of six poles are produced by the doublets parallel coupling gaps and a microstrip ring, and the other two are due to the employment of the CSRR and series gap. Two latterly added transmission poles lay exactly at the lower and upper edges of the filter. Table III summarizes the comparison of the proposed filter with other reported UWB filters. At most frequencies within the passband, the measured insertion loss of the filter is less than 1.68 dB and the return loss greater than 14.7 dB. Also, both simulation and measurement show that the 20 dB upper stopband extends at least up to 14.7 GHz. The difference between measured and simulated result is due to the feed lines and SMA connectors. As illustrated in Figure 9, the group delay is less than 0.5 ns in upper band and 1.5 ns in lower band of the proposed filter and maximum variation is about 1ns within the simulated wide passband.

5. Conclusion

The proposed UWB filter has six transmission poles. As a result, a compact and sharp rejection ultra-wideband (UWB) microstrip bandpass filter is realized. With the use of left-handed metamaterial structure, we achieve the necessary flexibility to obtain high levels of rejection, low insertion loss, and a compact size, simultaneously. The proposed UWB bandpass filter exhibits the passband of 3.4–10.15 GHz, an insertion loss smaller than 1.24 dB and 1.68 dB in simulated and measured results respectively and a return loss more than 17 dB and 16 dB in simulated and measured results respectively. In addition, the FCC's indoor limit is satisfied quite well. Meanwhile, a wide upper-stopband with the attenuation higher than 20 dB in the range of 10.15 to 14.7 GHz is achieved.

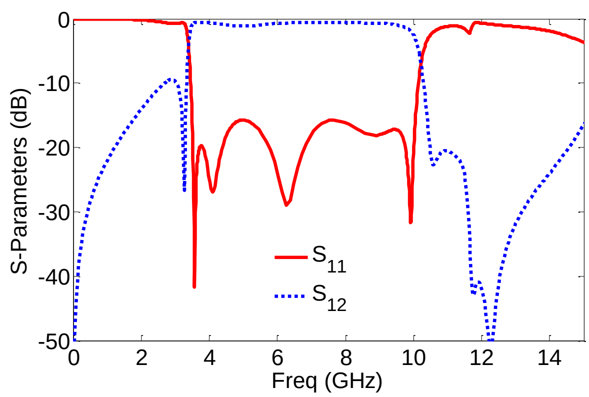

Fig. 6. Simulated frequency responses of the proposed UWB filter.

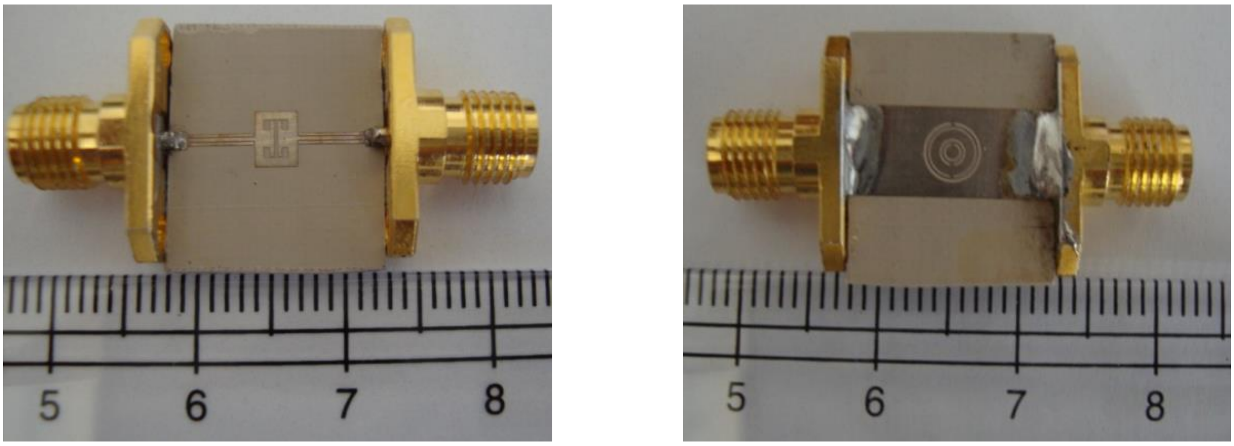

Fig. 7. Top and bottom views of the fabricated UWB filter.

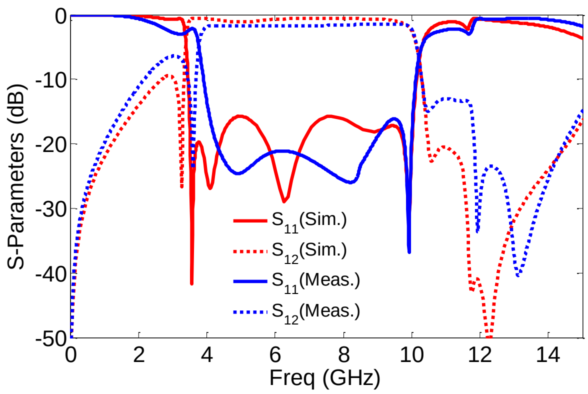

Fig. 8. Simulated and Measured frequency responses of the proposed UWB Filter.

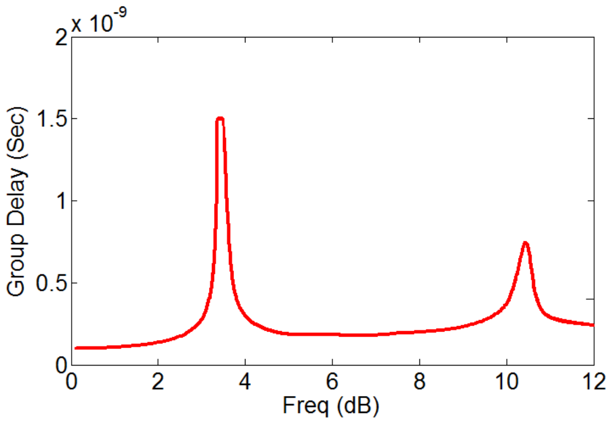

Fig. 9. Simulated Group delay of the proposed UWB Filter (maximum group delay variation 1ns).

Table III. Comparison with Other Works in Performance

Reference number	FWB (%)	IL (dB)	RL (dB)	Size (λ_g^2)
[7]	80	< 1.87	> 10.93	0.61×0.61
[9]	102.8	< 0.97	> 10.31	1.2×0.56
[15]	100	< 1.43	> 11.6	0.28×0.26
[20]	122	< 1.5	> 10	0.75×0.48
[26]	97.2	< 0.361	> 10	0.62×0.16
[27]	103.2	< 0.55	> 14	0.94×0.63
This Work	100	< 1.68	> 16	0.73×0.25

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