A Compact Ultra-Wideband Filter Based on Left Handed Transmission Line by Using Complementary Split Ring Resonators and Series Capacitor

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***Abstract*- A compact and sharp rejection UWB microstrip bandpass filter is developed using of left handed metamaterials. For realizing a backward-wave propagation medium, two split ring resonator (CSRR) in the back substrate side and also one series capacitor etched in the host line, are used to produce a negative effective ε and μ, simultaneously. Moreover, two doublets parallel coupling gaps is placed at each side of the series capacitor, in the proposed structure. In comparison with the other similar filters, 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. On top of that, using two CSRRs and series capacitor 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 and fabricated which exhibits extremely sharp rejection skirts around the target passband. Its passband covers 3.67 to 10.42 GHz and its measured 3 dB fractional bandwidth is about 95.8%. To the best of our knowledge, the size of proposed ultra-wideband filter is more compact in comparison with known similar filters.**

***Index Terms*-** Complementary split ring resonator (CSRR), Doublets parallel coupling gaps, Left handed transmission line (LHTL), Metamaterial, Ultra-wideband bandpass filter (UWBF).

I. INTRODUCTION

Recently, much attention has been paid to the development of UWB bandpass filters (BPFs), since the US Federal Communications Commission (FCC) released UWB spectrum (3.1-10.6 GHz) for unlicensed use [1]. The UWB radio systems are very promising, since the transmission data rates of the UWB systems are greater than those of current wireless local area network (WLAN) systems. The UWB bandpass filter (BPF) is one of the key passive components in UWB systems, and great efforts have been done to study different types of UWB filters. Therefore, several types of wideband BPFs have been researched using different structures [2]-[18]. The previous conventional UWB bandpass

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filters, mostly, were designed by using multiple-mode resonator (MMR), parallel coupled microstrip line (PCML) and defected ground structure (DGS) in their antenna layout. Wide bandwidth, multi-transmission poles, sharp lower and upper edges, compact size and good electrical performance are the most important characteristics that should be considered in a 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.

On the other hand, in the past few years, there has been a rising interest in the field of metamaterials especially composite right/left handed (CRLH) structures, 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 [19] such a media were not artificially fabricated until 2000 [20]. As metamaterials are frequency-selective structures by nature, their application to the design of compact microwave filters and diplexers seems to be straightforward. These structures can be realized in different ways. Because such devices require resonant elements, the preferred approach for the synthesis of filters and diplexers based on metamaterials is the resonant-type approaches.

In this paper, we propose a compact UWB bandpass filter using a series capacitor and CSRRs. When two doublets parallel coupling gaps in both input and output are arranged with a series capacitor, it exhibits a significantly widened passband. Also adding CSRRs, sharpen the rejection skirts at the lower and upper edges of the filter passband. As a result, the proposed UWB filter shows six transmission poles within its pass-band covering 3.67-10.42 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 14 GHz. The simulation results of the ultra-wideband filters are carried out by using an electromagnetic simulator, i.e., Agilent ADS simulator. The measured frequency response of the designed filter shows good agreement with the theoretical prediction, and also the FCC's indoor limit is well satisfied. Moreover, the proposed UWB filter has compact size and the FCC's indoor limit is well satisfied.

II. COMPLEMENTARY SPLIT RING RESONATOR (CSRR)

Metamaterial is an artificial effectively homogeneous electromagnetic structure with negative values of ε and μ, simultaneously. 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 split ring resonators (SRR) and complementary split ring resonators (CSRR) are useful components for the synthesis of narrowband and wide-bandpass filters [21]. Split ring resonators, originally proposed by Pendry et al. [22], have attracted great interest among researchers in electromagnetics and

(a)

(b)

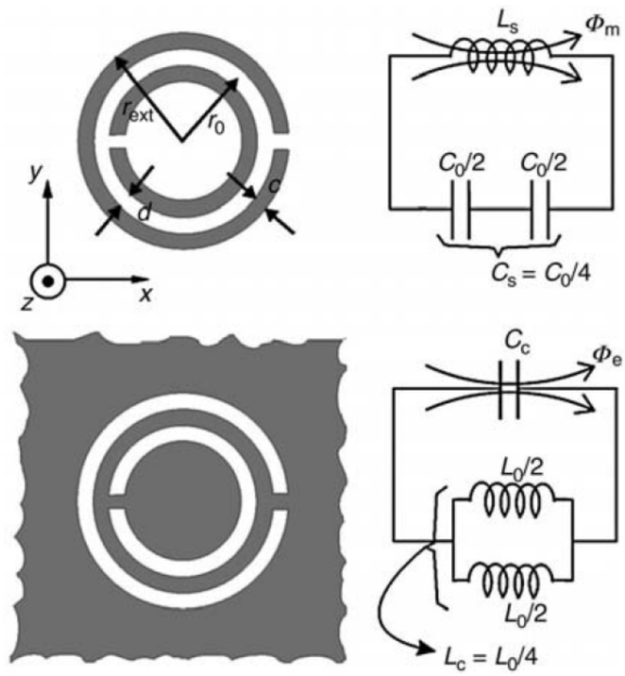


Fig. 1. Topologies of (a) the SRR and (b) CSRR, and their equivalent circuit models [21].

microwave engineers due to their potential applications to the synthesis of metamaterials with negative effective permeability. From a duality argument, complementary split-ring resonators were introduced by Falcone *et al.* in 2004 as new metamaterial resonators and have been proven to exhibit negative permittivity [23]. Later the characteristics for the SRRs and CSRRs including their equivalent-circuit models have been studied and developed extensively in which the SRRs are considered as resonant magnetic dipoles that can be excited by an axial magnetic field, while the CSRRs are shown to behave as electric dipoles, which need an axial electric field excitation [21]. Their applications to planar miniaturized microwave devices such as filters, diplexers, and couplers were then proposed and investigated [4], [24]-[25]. The fact that such resonators are electrically small and exhibit an effective permittivity or permeability which is negative in a narrow band above their resonant frequency is their key property. As elements able to generate a negative effective permittivity, CSRRs are also expected to produce controllable stopbands when etched in planar transmission lines and tuned at different frequencies. This is necessary to achieve high electric coupling between line and CSRRs, which is in turn of interest to obtain high levels of rejection in the forbidden band. In order to synthesize a left-handed medium, additional element able to provide the required negative effective 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.

The intrinsic circuit model for a CSRR (dual of the SRR model) is shown in Fig. 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. In the circuit model shown

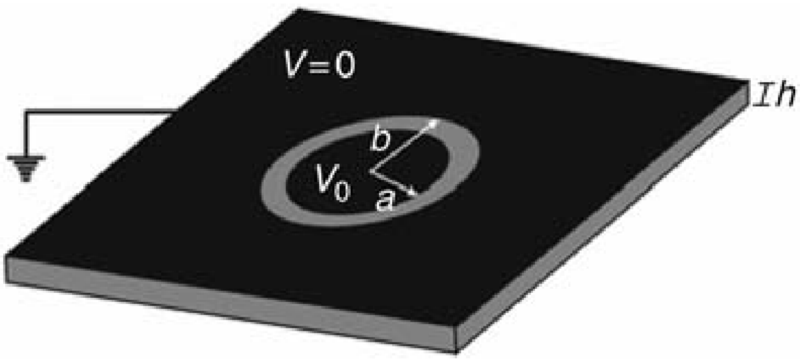


Fig. 2. The capacitance and inductance of the CSRR is approximately equal to that corresponding to a metallic disk of radius $a = r_0$-$c/2$ surrounded by a ground plane at a distance b-$a = c$, r_0 is the averaged radius of the CSRR and c is the width of the slots. The dielectric substrate is characterized by its permittivity ε and thickness h [21].

in Fig. 1, the inductance L_s of the SRR model is substituted by the capacitance, C_c, of a disk of radius r_0-$c/2$ surrounded by a ground plane at a distance c of its edge. Conversely, the series connection of the two capacitances $C_0/2$ in the SRR model is substituted by the parallel combination of two inductances connecting the inner disk to the ground. Each inductance is given by $L_0/2$, where $L_0 = 2\pi r_0 L_{pul}$ and L_{pul} is the per-unit-length inductance of the co-Planar Waveguide (CPW) connecting the inner disk to the ground. The capacitance C_c corresponds to a metallic disk of radius r_0-$c/2$ surrounded by a ground plane at a distance c [21]. Similarly, the inductance L_0 is in correspondence with a circular CPW structure of length $2\pi r_0$, strip width d, and slot width c [26]. An analytical approximate expression for C_c and L_0 in presence of a dielectric substrate is [26]:

$$C_C = \frac{\pi^3 \varepsilon_0}{c^2} \int_0^{\infty} \frac{\left[bB(kb) - aB(ka)\right]^2}{k^2} \left[0.5\left(1 + \frac{1 + \frac{\varepsilon}{\varepsilon_0}\left(\tanh(kh)\right)}{1 + \frac{\varepsilon_0}{\varepsilon}\left(\tanh(kh)\right)}\right)\right] dk \tag{1}$$

$$L_C = \frac{\pi^3 \mu_0}{4c^2} \int_0^{\infty} \frac{\left[bB(kb) - aB(ka)\right]^2}{k^2} dk \tag{2}$$

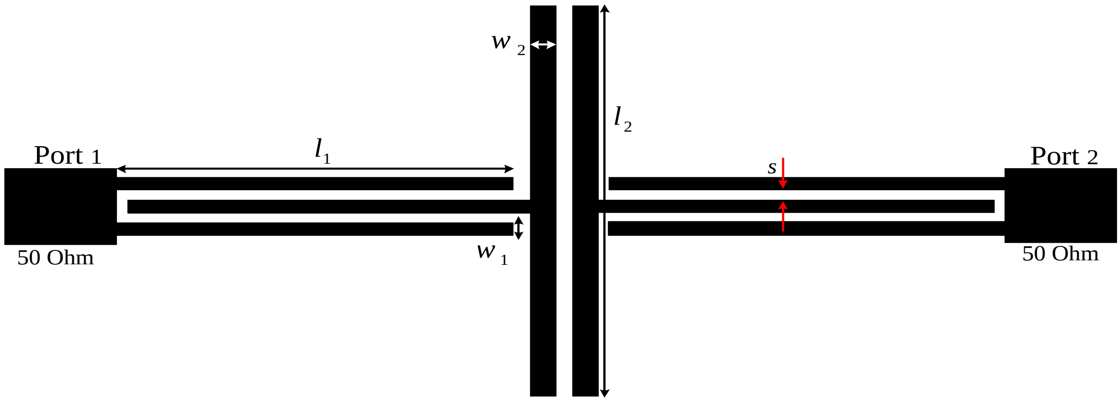
Where a, b, and h are geometrical variables defined in Fig. 2 and function B is defined as:

$$B(x) = S_0(x) J_1(x) - S_1(x) J_0(x) \tag{3}$$

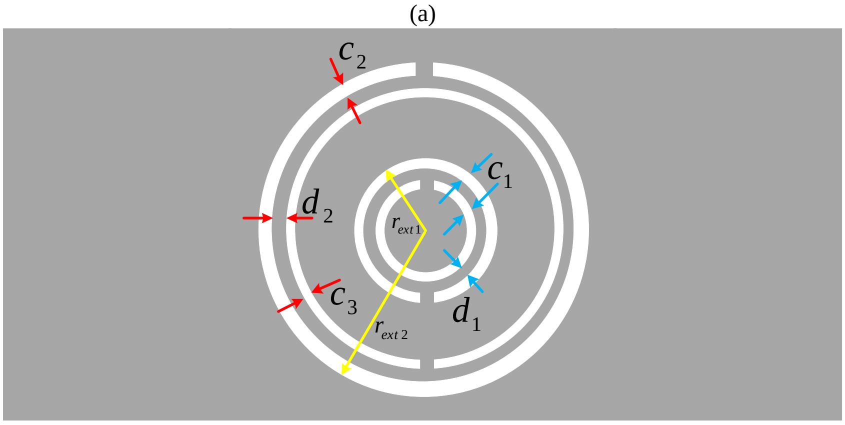
With S_n and J_n as the nth-order Struve's and Bessel's functions respectively. These expressions directly follow equation (1), which can be easily computed in few steps by using standard integration routines. Thus the resonance frequency of the CSRR is obtained from:

$$f_0 = \frac{1}{2\pi\sqrt{L_C C_C}} \tag{4}$$

The natural (although not exclusive) host transmission line for the implementation of one-dimensional metamaterials using CSRRs is the microstrip configuration. Due to the negative effective permittivity in the vicinity of CSRR's resonance, the signal is inhibited in a narrow band. In order to



(a)



(b)

Fig. 3. Configurations of the proposed UWB filter. (a) Top and (b) bottom layers.

synthesize the left-handed medium, additional elements which are able to provide the required negative permeability must be introduced to the structure, also. It was shown that the negative effective permeability can be achieved by etching series capacitive gaps in the host line. It was shown in [21] 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.

III. DESIGN OF UWB BANDPASS FILTER

The configuration of the proposed UWB filter has been shown in Fig 3. In the proposed design, a series capacitor is placed between two doublets parallel coupling gaps. Using two doublets parallel coupling gaps and a series capacitor, four pairs of resonant poles are produced and a significantly widened passband can be achieved.

The proper length of resonators and feed lines in the proposed filter structure, should be adjusted according to the desired frequency band. In Fig. 4, the influence of the length l_1 of the feed lines on the frequency response of the doublet parallel coupling gaps with series capacitor is shown. It can be seen that the impedance matching bandwidth of this filter can be simply adjusted by changing the

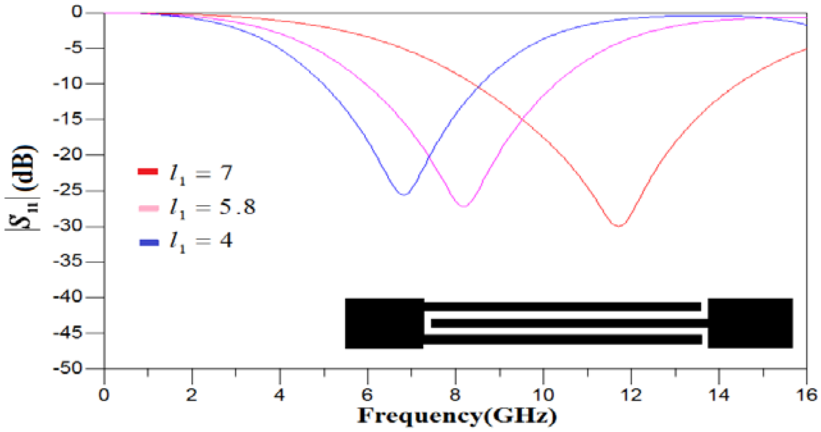


Fig. 4. Frequency response (|S_{12}|) of the microstrip ring with doublets parallel coupling gaps when the length l_1 of the parallel coupling gaps is 4mm, 5.8mm, and 7mm, respectively.

Table I. the dimensions of the proposed filter.

l_1	w_1	l_2	w_2	c_1	d_1	r_{ext1}	c_2	c_3	d_2	r_{ext2}
5.52	0.2	5.7	0.3	0.17	0.11	0.89	0.22	0.16	0.11	2.1

dimension of this gaps length. Three different lengths of l_1 are chosen, and they are 4.0mm, 5.8mm, and 7.0mm, respectively. It is seen that both the mid-band frequency and the bandwidth can be varied by changing the length of the feed lines.

Although placing two doublets parallel coupling gaps in each side of a series capacitor has an excellent performance over the pass-band, but its attenuation slope in the stop-band is quite slow. In order to sharpen the attenuations near the pass-band, in the other word to increase the bandwidth and also add the other two transmission poles in the pass-band, CSRRs in the back substrate sides of the proposed UWB filter are used. The CSRRs with series capacitor provide two transmission poles at the lower and upper edges 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. In Fig. 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. It demonstrates that how the impedance matching bandwidth of the proposed filter can be simply adjusted by changing the dimension of the gaps length. Three different lengths of $l_1 = 3,4,$ and 5mm are chosen. It is seen that both the midband frequency and the bandwidth can be varied by changing the length of the feed lines. Consequently, the proposed UWB filter shows six transmission poles within its pass-band covering 3.67-10.42 GHz and also sharp attenuations near the passband are realized.

For easy fabrication of the filter, all the gap widths between the strips in the filter are chosen as 0.1 mm, and the strip widths of the parallel coupling gaps are chosen as 0.2mm. The layout of proposed UWB filter is shown in Fig. 3. The filter Dimensions can be seen in table I where all of them are in

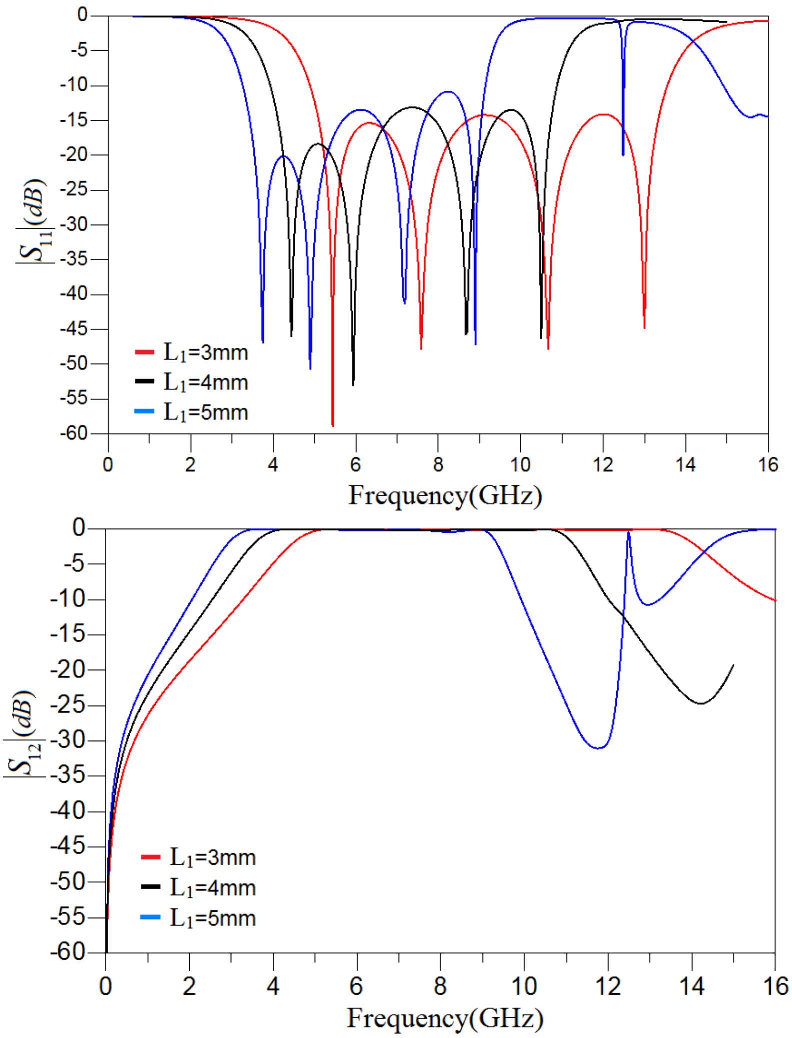


Fig. 5: Frequency response ($|S_{11}|$ and $|S_{12}|$) of the microstrip series capacitor with doublets parallel coupling gaps when the length l_1 of the parallel coupling gaps is 3mm, 4mm, and 5mm, respectively. Other dimensions are: w_1 = 2.8 mm, l_2 = 4 mm, w_2 = 0.6 mm.

millimeters. Accordingly the total size of the filter is less than 11.8 mm × 5.7 mm. The substrate is chosen to be RT/Duroid6006 with the relative permittivity 6.15, the loss tangent tanδ=0.0027 and the thickness of 0.635 mm. Also in the simulations, the metallic loss have been taken into account, using the conductivity of copper σ =5.8×10^{7} S/m.

IV. SIMULATION AND MEASUREMENT RESULTS

A microstrip Ultra wideband bandpass filter is designed, simulated and fabricated. A photograph of the fabricated UWB filter is shown in Fig. 6, which demonstrates the quite small size of the filter. The frequency responses of the proposed UWB band-pass filter are simulated by Agilent ADS simulator and also are measured by employment of a network analyzer HP8510C (Fig. 7). Both two results are in good agreement with each other. The proposed filter exhibits the passband of 2.83–10.06 GHz, an insertion loss smaller than 1 dB, and a return loss more than 10 dB in simulated and measurement

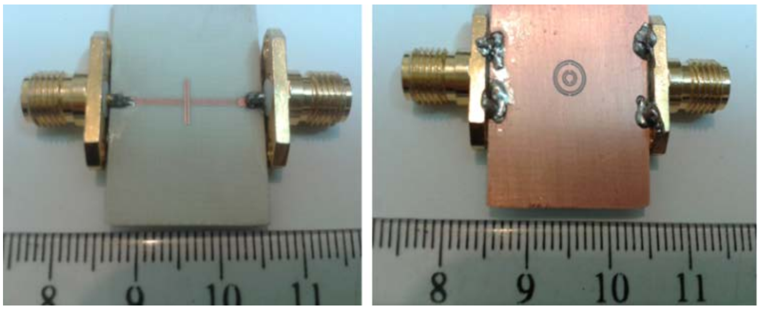


Fig. 6. Top and bottom views of the fabricated UWB filter.

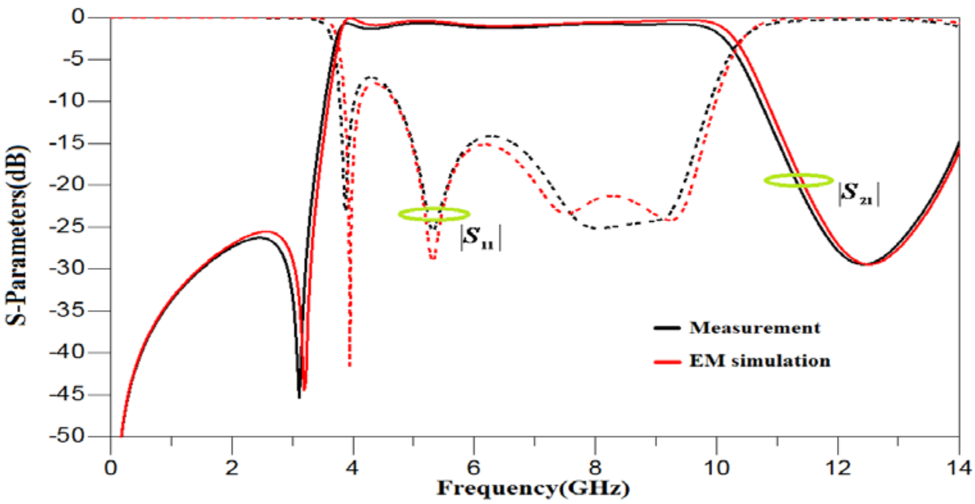


Fig. 7. Simulated and Measured frequency responses of the proposed UWB Filter.

results. The results show that the proposed BPF filter has a 3 dB fractional bandwidth of 95.8% from 3.67 to 10.42 GHz. Six transmission poles are observed within the passband covering approximately 3.67-10.42 GHz. Four poles are produced by the doublets parallel coupling gaps and a series capacitor, and two poles are due to the employment of the CSRRs. two latterly added transmission poles lay exactly at the lower and upper edges of the filter. Also the proposed filter group delay (Fig. 8) is less than 0.4ns in upper band, 0.9 ns in lower band and maximum variation of about 0.5 ns within the measured wide pass-band. On top of these satisfying specifications, the FCC's indoor limit is satisfied quite well. Meanwhile, a wide upper-stopband with the insertion loss higher than 20 dB in the range of 10.42 to 14 GHz is achieved. Overall the measurement is in agreement with the simulation while the small discrepancy may due to the e influence of SMA connectors and the fabrication errors.

Table II summarizes the comparison of the proposed filter with other reported UWB filters. This comparison shows that the proposed filter has a smaller size than the others and also it could maintain its wide passband bandwidth which is because of the left handed metamaterial operation.

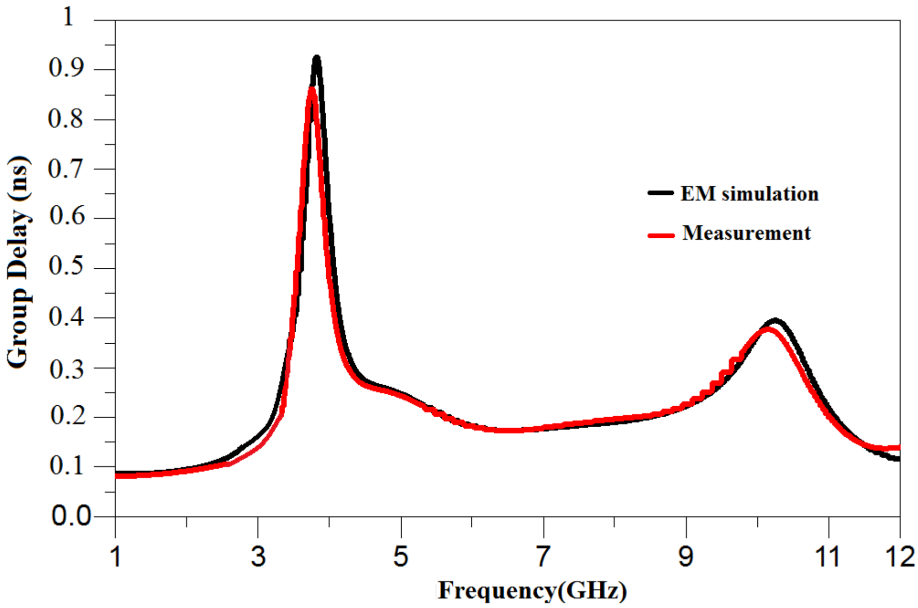


Fig. 8. Simulated and measurement Group delay of the proposed UWB Filter.

Table II. Performance Comparisons of the Recent Filters with the Others.

Reference number	Fractional bandwidth	Upper Stop Band (GHz)	Insertion loss (IL)	Return loss (RL)	Size $\lambda_g \times \lambda_g$
[8]	102.8%	10.7-15.7(20dB)	min> -0.97dB	> 10.31dB	1.2×0.56
[12]	80%	7-13.2(19dB)	min> -1.87dB	> 10.93dB	0.61×0.61
[13]	122%	11.1-18(21.5dB)	min> -1.5dB	> 10dB	0.75×0.48
[14]	122%	11.32-20(18dB)	min> -1.5dB	> 10 dB	0.76×0.49
This Work	95.8%	10.42-14 (20dB)	min> -1dB	> 10dB	0.57×0.24

V. CONCLUSION

A compact UWB microstrip filter with six transmission poles, which exhibit extremely sharp rejection skirts around the target passband, has been proposed and designed using the left handed transmission line (LHTL). With the use of CSRRs, we achieve the necessary flexibility to obtain high levels of rejection and low insertion loss, simultaneously. The proposed UWB bandpass filter exhibits the passband of 3.67–10.42 GHz, an insertion loss smaller than 1 dB and a return loss more than 10 dB in simulated and measurement results. The filter is compact in size, and the minimum strip width and gap width are 0.2mm and 0.1mm, respectively. Therefore, easy fabrication of the filter at low cost is allowed. On top of that the FCC's indoor limit is satisfied quite well. Meanwhile, a wide upper-stopband with the insertion loss higher than 20 dB in the range of 10.42 to 14 GHz is achieved.

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