A Highly Compact UWB Bandpass Filter using Via-less CRLH TL

Uday Kumar, Dileep Kumar Upadhyay

Abstract – **The composite right/left handed transmission line (CRLH TL) based novel and highly compact ultra-wideband (UWB) bandpass filter (BPF) is proposed in this paper. The CRLH TL consists of single unit-cell only. The unit-cell of CRLH TL is designed using via-less, single layer, CPW-fed series interdigital capacitor in shunt with the shorted inductive stubs to ground. The absence of via due to the use of CPW-fed, ease the fabrication processes and makes the circuit more practically feasible as compared to the conventional technique of design of CRLH TL using via. The proposed UWB BPF is highly compact in size, 11.9 mm × 4.9 mm. The filter exhibits the insertion-loss (|S_{21}|) less than 0.4 dB and return-loss (|S_{11}|) better than 11.4 dB throughout the frequency band, 3.1 GHz to 10.6 GHz, which fulfills the UWB criteria of FCC. The performance and physical parameters of proposed UWB BPF are compared with the earlier reported UWB BPFs. An equivalent lumped circuit model of the UWB BPF is obtained by Ansoft Designer. All the simulated results are extracted using method of moments (MoM) based electromagnetic (EM) simulator, IE3D and compared by the measured results. All measured results show the close similarity with the simulated results.**

Keywords – **Composite Right/Left Handed Transmission Line, Coplanar Waveguide, Interdigital Capacitor, Ultra-Wideband Bandpass Filter.**

I. INTRODUCTION

Developments of UWB microwave circuits become an emerging and challenging research field for researcher since the Federal Communications Committee (FCC) authorized the frequency band from 3.1 GHz to 10.6 GHz for unlicensed use in Feb. 2002 for short range wireless communication [1]. For design and developments of UWB BPFs, several methods and techniques have been used to reduce the size, to improve the performance and to ease the fabrication complexity/steps. For the design of UWB components, lots of efforts and challenges such as high selectivity, low insertion-loss and constant group delay are required as compared to the narrowband components.

A compact (13 mm × 8.5 mm) UWB BPF based on CRLH TL unit-cell designed by split ring resonator as defected ground is reported in [2]. A multimode resonator and conventional CRLH TL unit-cell with shorted inductive stub based UWB BPF reported in [3], is small in size, 16.4 mm × 4.8 mm and good in performance. By cascading the interdigital line with three defected ground structures the CRLH TL based UWB BPF [4], has the relatively larger in size 30 mm × 15 mm and poor insertion-loss 1.5 dB. The UWB BPF based on CRLH TL reported in [5], operates over 4 GHz to 9.5 GHz, has relatively larger in size (30 mm × 8.5 mm), poor out-of-band rejection level and insertion-loss (1.5 dB). However, the reported CRLH TL based UWB BPFs [2-5], use the via to get the shunt inductance to realize the CRLH TL. The requirements of the drilling and soldering to realize the via, unnecessarily leads to the more fabrication steps and costly ground plane processing. A compact via-less coplanar waveguide (CPW) fed UWB BPF reported in [6] is small in size (18.4 mm x 4.5 mm) but has relatively large in size, used an expensive substrate (RT/duroid 5880) and complex geometry, which requires the difficult, tight and great care during fabrication processes as compared to proposed UWB bandpass filter.

The fractal shaped UWB BPF [7], the multimode resonator based UWB BPF [8], cascading bandpass and bandstop filters based UWB BPF [9], UWB BPF based on cascading the stepped-impedance resonators [10], broadside coupled structures based UWB BPFs [11-12], and defected ground structure based UWB BPF [13] are considered here to compare the physical parameters and performance of the UWB BPFs [7-13], to the proposed UWB BPF.

In this paper, authors propose a novel compact UWB BPF based on CPW-fed via-less CRLH TL. The single unit-cell CRLH TL is designed using series interdigital capacitor in shunt with the shorted inductive stubs. Due to the use of CPW-fed, the via is not required as signal and ground planes are in same plane. So proposed planar UWB BPF ease the fabrication processes and reduces the costly ground plane processing as compared to the conventional technique of design of CRLH TL unit-cell, where via is used to short circuit the inductive stub. The proposed filter is compact in size (11.9 mm × 4.9 mm), shows the good S-parameters characteristic ($|S_{21}| < 0.4\,dB,\ \ |S_{11}| > 11.4\,dB$) and constant group delay (maximum deviation, 0.8 ns) throughout the UWB passband (3.1 GHz to 10.6 GHz). The equivalent circuit model of the proposed UWB BPF is obtained using circuit design tool of Ansoft Designer. The simulation results are obtained using MoM based commercially available EM simulator, IE3D. The simulated results, equivalent circuit model results and measured results of UWB BPF show the good similarity.

II. THEORY OF UWB BPF

The proposed UWB BPF is based on CRLH TL. The CRLH TL is realized by combination of pure right handed (PRH) and pure left handed (PLH) transmission lines [14].

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Uday Kumar is with the Department of Electronics and Communication Engineering, Birla Institute of Technology Mesra, Ranchi, India, E-mail: ranjanuday333@gmail.com

Dileep Kumar Upadhyay is with the Department of Electronics and Communication Engineering, Birla Institute of Technology Mesra, Ranchi, India, E-mail: dileep_18@rediffmail.com

The PRH TL is obtained by series inductor (L_R) in shunt with the parallel capacitor (C_R), which shows the lowpassfilter response whose cut-off frequency is given by $f_{CR} = \frac{1}{2\pi\sqrt{L_R C_R}}$. The PLH TL is obtained by series capacitor (C_L) in shunt with the parallel inductor (L_L), which shows the highpass filter response whose cut-off frequency is given by $f_{CL} = \frac{1}{2\pi\sqrt{L_L C_L}}$. Since CRLH TL is realized by combination of PLH TL and PRH TL, so when $f_{CR} < f_{CL}$, it acts as a bandpass filter.

The equivalent circuit model of CRLH TL consists of series left handed (LH) capacitance (C_L) and right handed (RH) inductance (L_R) in shunt with the parallel LH inductor (L_L) and RH capacitor (C_R). The relationships between circuit elements and frequency of the CRLH TH are given as follows [14].

$$f_{se} = \frac{1}{2\pi\sqrt{L_R C_L}} \tag{1}$$

$$f_{sh} = \frac{1}{2\pi\sqrt{L_L C_R}} \tag{2}$$

For balanced CRLH TL,

$$f_{se} = f_{sh} = f_0 = \sqrt{f_{se}\, f_{sh}} \tag{3}$$

$$f_L = \frac{1}{2\pi\sqrt{L_R C_L}} \tag{4}$$

$$f_U = \frac{1}{2\pi\sqrt{L_R C_L}} \tag{5}$$

where: f_{se}, f_0, f_L, f_{sh} and f_U are series resonance frequency, centre frequency, lower end frequency, shunt resonance frequency and upper end frequency respectively.

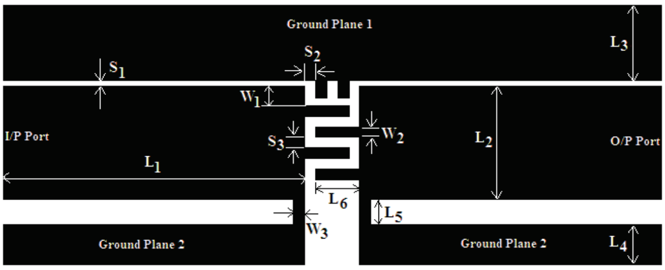

Fig. 1. Layout of the proposed UWB BPF

III. DESIGN OF PROPOSED UWB BPF

The design layout of the proposed UWB BPF is depicted in Fig. 1. The filter is excited by via-less asymmetric CPW-fed. The asymmetric CPW fed is used to get the proper impedance matching for required response of the filter. The series LH capacitance (C_L) is obtained by realizing four fingers interdigital capacitor and parallel LH inductor (L_L) is obtained by shorting the stubs of length (L_5) to ground plane 2. The series RH inductor (L_R) and parallel RH capacitor (C_R) are generated by transmission lines of length (L_1) and the slot (S_1) between the transmission lines and ground plane 1 respectively. The proposed UWB BPF is designed on low cost easily available FR4 substrate withrelative permittivity ($\varepsilon_r = 4.4$), loss tangent ($\tan\delta = 0.02$) and thickness ($\boldsymbol{h = 1.6\ mm}$). All physical parameters are obtained by parametric study and equivalent lumped circuit model of the geometry.

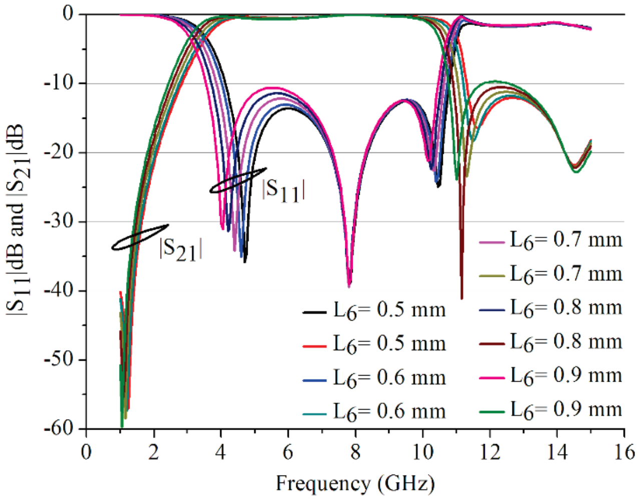

Fig. 2. Effects of variation of interdigital finger length, L_6 on S-parameters

The parametric studies on proposed UWB BPF are performed and their effects on the S-parameters are investigated to get the optimized physical dimensions. Effect of variation of interdigital finger length, L_6 on S-parameters is shown in Fig. 2. The required -3dB bandwidth, 3.1 GHz to 10.6 GHz is observed for $L_6 = 0.8$ mm. Higher value of, L_6 deteriorates the S-parameters performance while lower values of it do not meet the required bandwidth. The effects of variation of gap, S_1 between the transmission line and ground plane 1 on S-parameters characteristics is shown in Fig. 3.

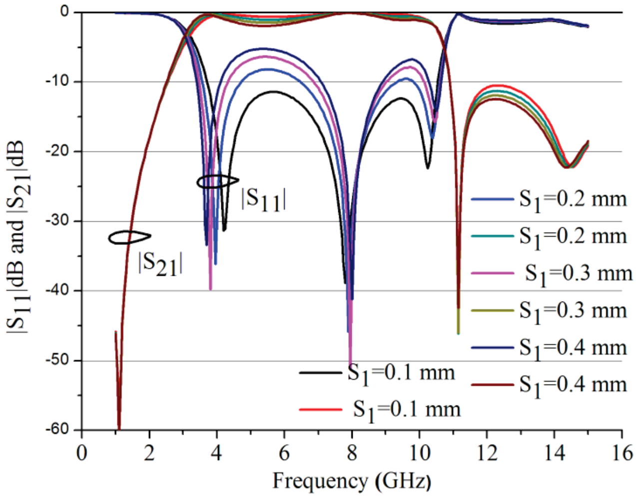

Fig. 3. Effects of variation of gap, $\boldsymbol{S_1}$ on S-parameters

The optimized value of S_1 is observed at 0.1 mm. From the Fig. 3, it can be seen that as the value of S_1 increases, the return-loss and insertion-loss are deteriorated while maintaining almost constant bandwidth. Fig. 4 depicts the effects of variation of stub length, L_5 on S-parameters response. From the Fig. 4, it can be observed that the change in stub length L_5 does not change the -3dB passband bandwidth. The optimized value of L_5 is observed at 0.5 mm. Decrease in the value of L_5 results the improvement in the return-loss at frequency 5.5 GHz while deterioration at frequency 9.4 GHz. The vice-versa effect is observed while increasing the value of L_5. So, the optimum value of L_5 is chosen by compromising the effect of S-parameters on both the frequencies, i.e. 5.5 GHz and 9.4 GHz. The effects of variation of length L_1 on S-parameters isshown in Fig. 5.

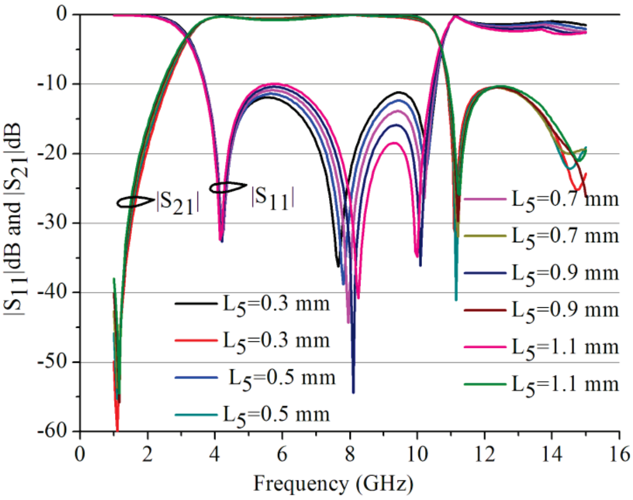

Fig. 4. Effects of variation of stub length, L_5 on S-parameters

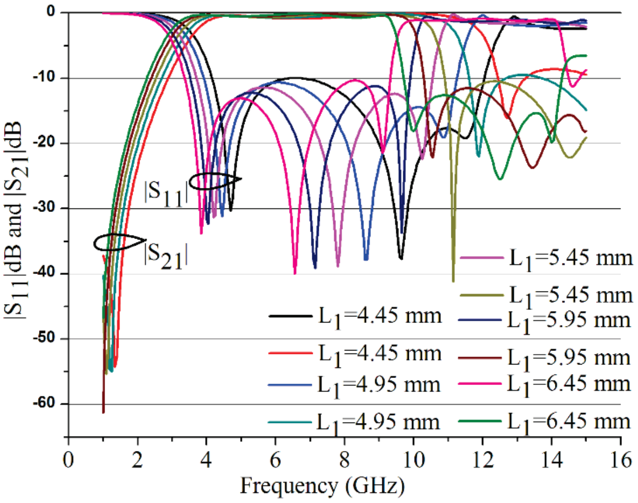

Fig. 5. Effects of variation of length, L_1 on S-parameters.

TABLE 1
OPTIMIZED PHYSICAL PARAMETERS OF UWB BPF SHOWN IN FIG. 1

Parameters	L_1	L_2	L_3	L_4	L_5	L_6
Dimensions (mm)	5.45	2.14	1.43	0.75	0.5	0.8
Parameters	W_1	W_2	W_3	S_1	S_2	S_3
Dimensions (mm)	0.37	0.2	0.2	0.1	0.2	0.2

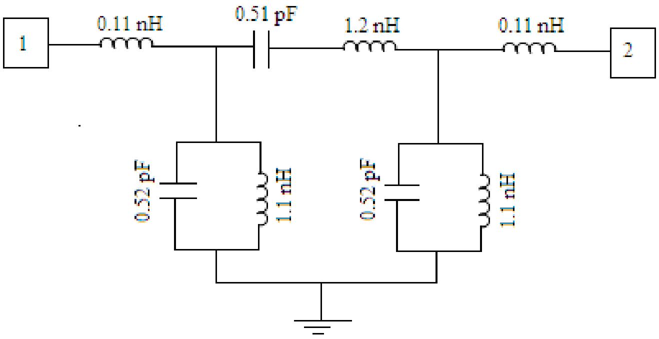

Fig. 6. Equivalent lumped circuit model of the UWB BPF

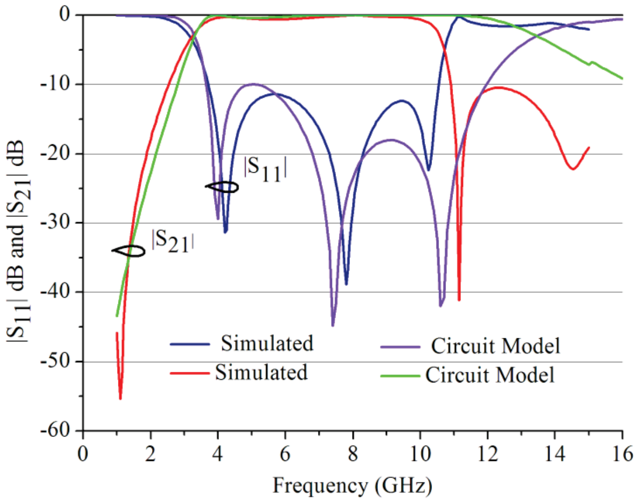

Fig. 7. Comparative S-parameters vs. frequency plot of simulated and equivalent lumped circuit model

The increase in the value of L_1 shifts the cutoff frequencies to the higher end of frequency. Hence considering the required bandwidth and return-loss the optimum value of L_1 is chosen to be 5.45 mm. All optimized physical dimensions of proposed UWB BPF depicted in Fig. 1 are listed in Table 1.

The equivalent lumped circuit model of UWB BPF given in Fig. 1, is shown in Fig. 6. In the equivalent circuit model, the mutual coupling between the individual components is not taken into considerations. The input and output inductance of value 0.11 nH each is generated because of the input and output transmission lines of length, L_1. A series capacitance of 0.51 pF is introduced by the interdigital capacitor. A series inductance of value 1.2 nH is generated because of the parasitic effect of interdigital capacitor. Two tank circuits shunted to the ground, each consists of inductance of 1.1 nH and capacitance of 0.52 pF are introduced because of the inductance associated by stub of length, L_5 shorted to ground plane 1 and capacitance associated by the gap, S_1 between transmission line and ground plane 2.

Fig. 7, shows the comparative simulated and equivalent lumped circuit model S-parameters results. The simulated results show that the filter exhibits insertion-loss less than 0.4 dB and return-loss greater than 11.4 dB throughout the desired frequency band, 3.1 GHz to 10.6 GHz. A close agreement between the circuit model and simulated results can be seen except at some higher frequency end, which may be arised because of the ignorance of effect of mutual coupling between the individual elements.

The simulated group delay response of the UWB BPF is constant throughout the passband as shown in Fig. 8. The group delay fluctuates between 1.5 ns to 0.7 ns, which show the maximum deviation of 0.8 ns throughout the desired frequency band. Because of the sharp transition of the curves from passband to stopband, relatively large variations in group delay are observed at both passband ends of the filter.

TABLE 2
COMPARISON OF PROPOSED UWB BPF TO THE REPORTED UWB BPFS

Ref.	S_{21} (dB)	S_{11} (dB)	Frequency Range (GHz)	Size (mm)	Area (mm^2)	Via
[2]	1.0	13	3.1-10.6	13 x 8.5	110.5	Yes
[3]	0.5	11	2.9-10.75	16.8 x 4.8	80.64	Yes
[4]	1.5	10	3.9-10.3	30 x 15	450	Yes
[5]	1.0	10	4.0-9.5	30 x 8.5	255	Yes
[6]	0.3	10	3.15-10.8	18.4 x 4.5	82.8	No
[7]	1.1	15.2	2.5-11	30 x 20	600	No
[8]	0.68	17	3.4 – 10.7	21 x 5.3	111.3	Yes
[9]	1.0	13	2.96 -10.43	42.3 x 12.3	520.3	Yes
[10]	2.0	10	3.1-10.6	28 x 15	520	Yes
[11]	1.0	14	2.8-10.9	30 x 20	600	Yes
[12]	1.0	11	3.1-10.6	25 x 30	750	Yes
[13]	2.5	15	0 - 18	26.2 x11.9	311.78	No
This work	0.4	11.4	3.1-10.6	11.9 x 4.9	58.31	No

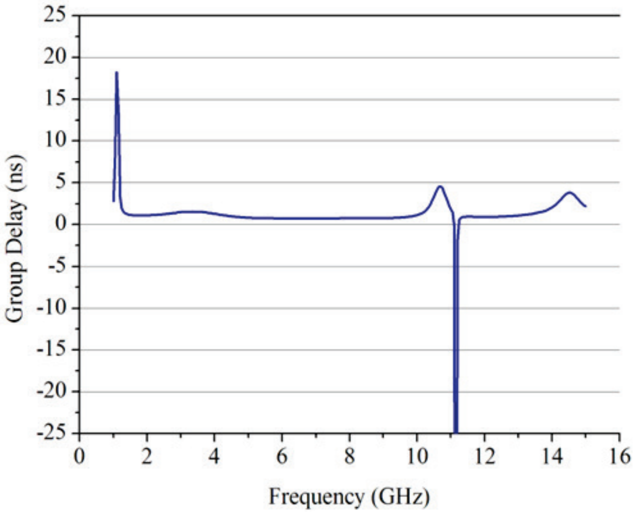

Fig. 8. Simulated group delay response of the UWB BPF

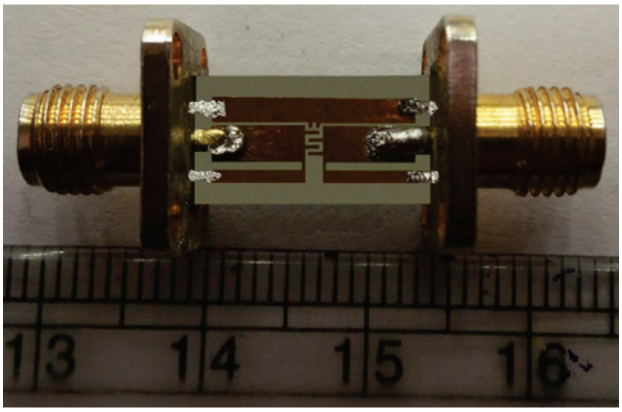

Fig. 9. Fabricated photograph of proposed UWB BPF

IV. EXPERIMENTAL RESULTS AND DISCUSSION

The proposed layout of the UWB BPF depicted in Fig. 1, is fabricated and tested. Fig. 9, shows the photograph of fabricated UWB BPF. Fig. 10, represents the comparative simulated, lumped circuit model and measured insertion-loss and return-loss verses frequency plot. The measured $|S_{11}|$ dB and $|S_{21}|$ dB results of the UWB BPF show that the filter exhibits the $|S_{21}|$ less than 0.65 dB and $|S_{11}|$ greater than 10.3 dB throughout the frequency band, 3.2 GHz to 10.9 GHz. The close similarity between the measured and simulated results can be seen, however a little deviation between the measured and simulated results can be seen which arises due to the consideration of finite ground plane, improper soldering and fabrication tolerances.

The comparative measured and simulated group delay plot of the UWB BPF is depicted in Fig. 11. A constant group delay is observed throughout the passband of the filter. The measured group delay deviates between 1.6 ns to 0.48 ns and hence the maximum deviation in the group delay is 1.12 ns. Table 2 summarizes the comparative data of proposed ultra-wideband bandpass filter to the best reported UWB bandpass filters.

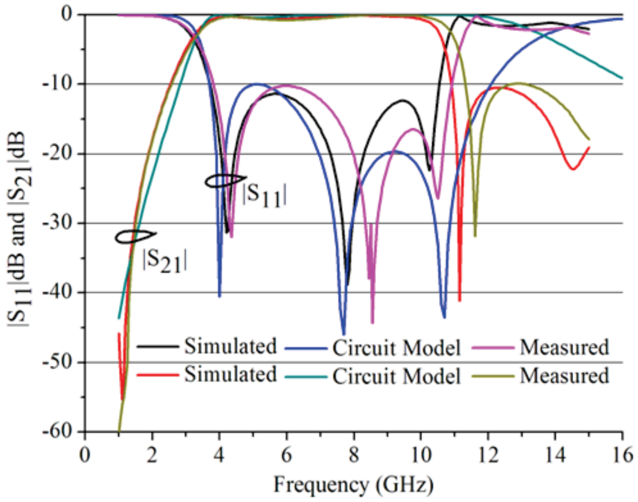

Fig. 10. Comparative simulated, circuit model and measured S-parameters vs. frequency plot of UBW BPF

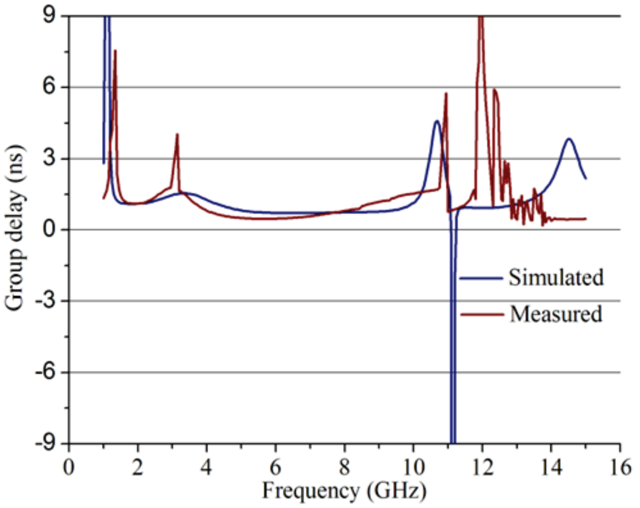

Fig. 11 Comparative simulated and measured group delay vs. frequency plot.

V. CONCLUSION

A novel highly compact UWB BPF designed and developed based on CRLH TL is presented in this paper. The filter is simple in profile structure and designed on via-less CRLH TL, which ease the fabrication process and reduces the expensive ground plane processing. The filter size is 11.9 mm × 4.9 mm. The filter exhibits the insertion-loss < 0.4 dB and return loss > 11.4 dB and, low and constant group delay (0.8 ns) response throughout the desired passband frequency band, 3.1 GHz to 10.6 GHz. Because of the compact in size, simple profile geometry structure, less fabrication steps and good performance, the proposed UWB BPF may be used in small sized wireless communication systems.

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