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Research Article

Design of UWB Bandpass Filter with Notched Band Using Distributed CRLH Transmission Lines

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Abstract: This study presents an Ultra-Wideband (UWB) filter with a notched band. The filter adopts novel Composite Right/Left-Handed (CRLH) Transmission Lines (TLs), the unit cell of which is theoretically analyzed to derive the design formulas. A model of the CRLH TLs is composed with distributed elements rather than lumped elements. Based on the results of the analysis, it is confirmed that the proposed structures are CRLH TLs. A UWB bandpass filter with a notched band is designed and fabricated using the induced formulas. The measurement results show that the fabricated UWB bandpass filter has an insertion loss of less than 3 dB, a bandwidth of 2.8-10.5 GHz and a rejection of greater than 27 dB at 5.75 GHz.

Keywords: Bandpass Filter (BPF), Composite Right/Left-Handed (CRLH) transmission line, notched band, Ultra-Wideband (UWB)

INTRODUCTION

In 2002, the Federal Communications Commission (FCC) released the frequency band of 3.1-10.6 GHz for Ultra-Wideband (UWB) communication. UWB systems with a high data rate, short range and short pulses have been rapidly developed for commercial purposes. Bandpass Filters (BPFs) for UWB systems are essential components and have thus been studied widely. Most UWB BPFs suffered from large overall sizes. Sharp rejection characteristics at 5.8 GHz are needed to avoid interference between UWB systems and Wireless Local Area Networks (WLANs). Therefore, a UWB system requires a compact BPF, including narrow bandstop notches.

Since the concept of Multiple-Mode Resonators (MMRs) used for UWB BPFs was initially proposed in (Zhu *et al*., 2005), many filters have been designed using MMRs. To implement a narrowband notch, a short-circuited stub-loaded MMR was used with a meander line slot on a feed line (Yang *et al*., 2008), the spur lines and embedded open-circuited stubs were implemented in the MMR (Lee *et al*., 2008) and the MMR was composed of a stub-loaded modified Stepped Impedance Resonator (SIR) and two identical interdigital feed lines (Gao *et al*., 2009). Three dumbbell-shaped stub-loaded MMRs and a one-arm-folded interdigital coupled line were used to obtain a notched band (Chen *el al*., 2010). A parasitic coupled line was embedded in a UWB BPF based on a stub-loaded MMR (Pirani *et al*., 2010). A notched UWB BPF was built up with a Coplanar Waveguide (CPW) MMR and microstrip/CPW surface-to-surface coupling lines. To obtain a notched band, Split Ring Resonators (SRRs) were embedded in the CPW MMR (Chen *el al*., 2011). The MMR was fabricated by loading three pairs of stepped-impedance stubs in a uniform resonator and to produce the notched band, two complementary split ring resonators etched on CPW feed lines (Honarvar and Sadeghzadeh, 2012).

Some UWB BPFs with notched bands have included a ground plane structure. The surface-coupled structures and Y-shaped shorted stub resonator on the ground were adopted as quasi-lumped circuit elements and two shorted lines were designed to generate notched bands (Huang *et al*., 2010). A compact UWB BPF with a notched band was introduced using a hybrid microstrip and CPW structure with a meander slotline structure embedded on the ground (Luo *et al*., 2010). A UWB notch-band BPF using multiple slotline resonators on the ground was presented in (Song *et al*., 2012). Recently, a compact band-notched UWB BPtF with microstrip/slotline ring resonators and microstrip short circuited stubs was presented in Cui *et al*. (2014). A stubs-loaded slotline MMR fed by two microstrip lines achieved a UWB bandpass characteristic and a notched band was created by loading a stub-loaded, dual-mode microstrip resonator to the slotline MMR (Guan *et al*., 2014). A UWB BPF with hybrid CPW feed-line and microstrip resonator structure was presented and a notched band was realized using a symmetric E-shaped slot-line and etching slots on a microstrip resonator (Zheng *et al*., 2014).

In this study, we present the design of a compact UWB BPF with a notched band. This is achieved using novel distributed Composite Right/Left-Handed

(CRLH) Transmission Lines (TLs), the dispersion characteristics of which are theoretically proven by using an even/odd-mode analysis method. The simulated and measured results of the proposed UWB BPF are in good agreement.

MATERIALS AND METHODS

Figure 1 shows the circuit model of a distributed CRLH TL unit cell for the notched UWB BPF. It cannot be described explicitly which elements make a Right-Handed (RH) TL or a Left-Handed (LH) TL in the distributed CRLH TLs. However, the π equivalent circuit of the unit cell can determine if the proposed unit cell is a CRLH TL unit cell. Because the circuit model is symmetrical, even/odd-mode analysis can be used to derive the π equivalent circuit and the transfer function. The even/odd-mode admittances of the distributed CRLH TL unit cell are as follows:

$$Y_{even} = j\left(Y_2 \frac{Y_2 \tan\theta_2 + Y_3 \tan\theta_3 + Y_4 \tan(\theta_4/2) + Y_5 \tan(\theta_5/2) + Y_6 \tan\theta_6}{Y_2 - (Y_3 \tan\theta_3 + Y_4 \tan(\theta_4/2) + Y_5 \tan(\theta_5/2) + Y_6 \tan\theta_6)\tan\theta_2} - \frac{Y_1}{\tan\theta_1} \right) \tag{1}$$

$$Y_{odd} = j\left(Y_2 \frac{Y_2 \tan\theta_2 + Y_3 \tan\theta_3 - Y_4 \cot(\theta_4/2) - Y_5 \cot(\theta_5/2) + Y_6 \tan\theta_6}{Y_2 - (Y_3 \tan\theta_3 - Y_4 \cot(\theta_4/2) - Y_5 \cot(\theta_5/2) + Y_6 \tan\theta_6)\tan\theta_2} - \frac{Y_1}{\tan\theta_1} \right) \tag{2}$$

The series and shunt branch elements of the π equivalent circuit in Fig. 2a are as follows:

$$Y_a = Y_b = Y_{even} \tag{3}$$

$$Y_c = \frac{Y_{odd} - Y_{even}}{2} \tag{4}$$

If $Y_a>0$ and $Y_c<0$, the distributed CRLH TL unit cell operates as a Right-Handed (RH) TL, as shown in Fig. 2b. If $Y_a<0$ and $Y_c>0$, the distributed CRLH TL unit cell operates as a Left-Handed (LH) TL, as shown in Fig. 2c.

By using the Bloch-Floquet theory, the dispersion relation and characteristic impedance of the unit cell can be expressed as (Pozar, 2012):

$$\gamma(\omega) = \frac{1}{d}\cosh^{-1}(A) \tag{5}$$

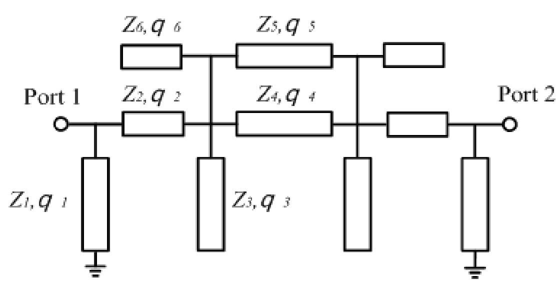


Fig. 1: Distributed CRLH TL unit cell for notched UWB BPF

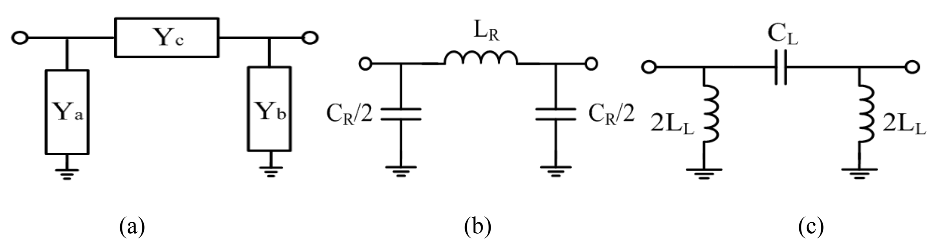


Fig. 2: (a): π equivalent circuit of distributed CRLH TL unit cell; (b): Equivalent circuit when Y_a, $Y_b>0$ and $Y_c<0$; (c): Equivalent circuit when Y_a, $Y_b<0$, and $Y_c>0$

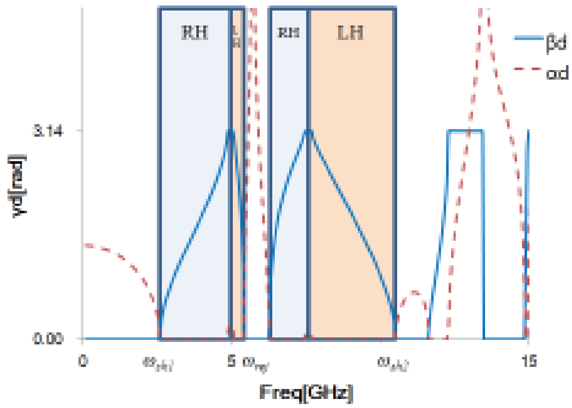
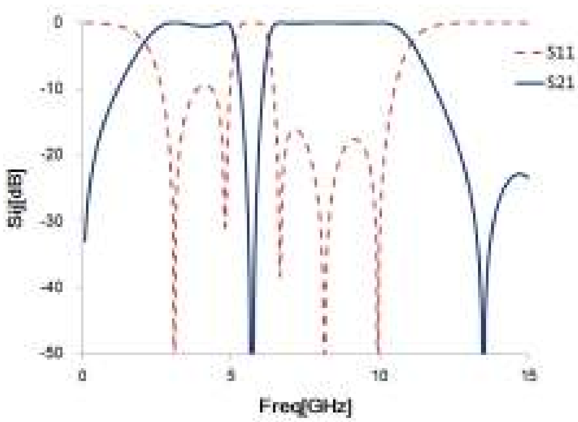
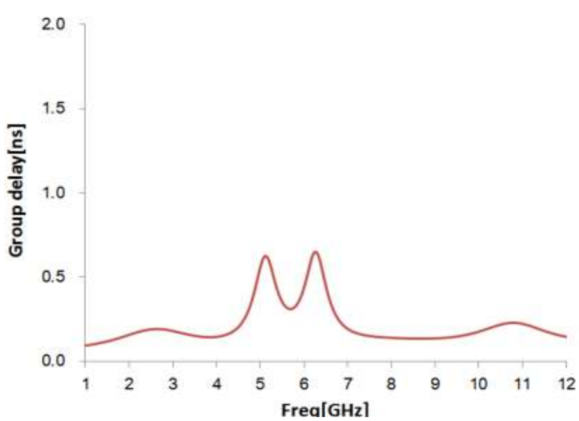


Fig. 3: Dispersion and attenuation diagram of distributed CRLH TL unit cell



(a)



(b)

Fig. 4: Frequency responses of the distributed CRLH TL unit cell; (a): Amplitude; (b): Group delay

$$Z_B(\omega) = B\Big/\sqrt{A^2 - 1} \tag{6}$$

where, d is the length of the unit cell, Z_B is the characteristic impedance normalized to the port impedance, Z_0 and:

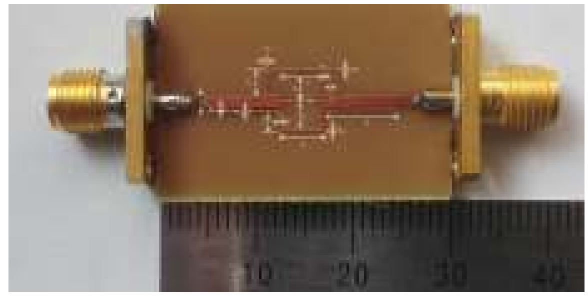


Fig. 5: Photograph of the fabricated UWB BPF

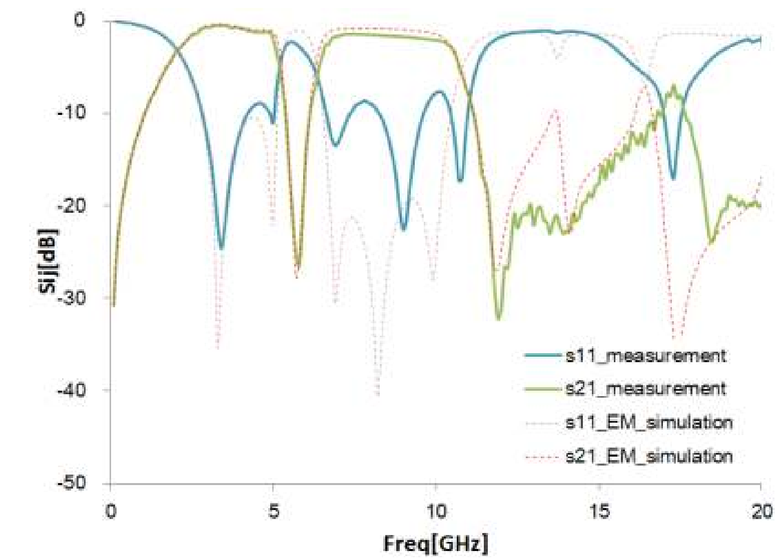
$$A = 1 + \frac{2Y_{even}}{Y_{odd} - Y_{even}} \tag{7}$$

$$B = \frac{2}{Y_{odd} - Y_{even}} \tag{8}$$

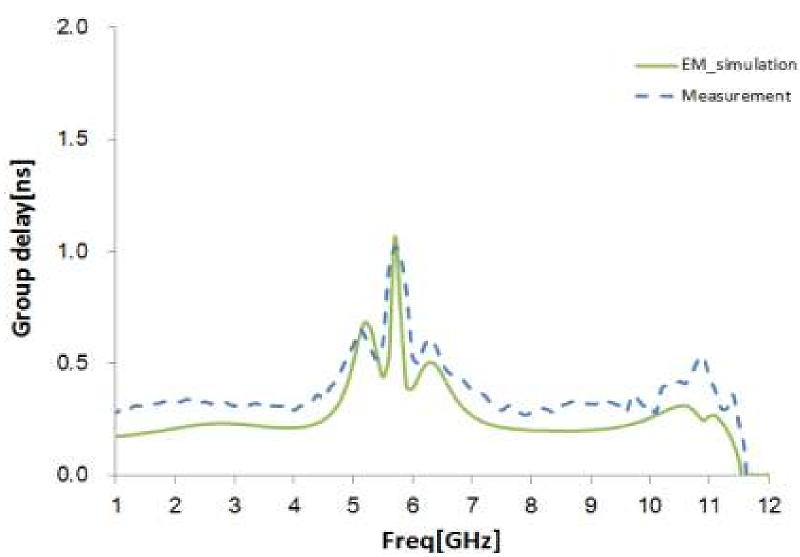
The dispersions and attenuations of the distributed CRLH TL unit cell are shown in Fig. 3, when $\theta_1 = \theta_4 = 60°$, $\theta_2 = \theta_3 = 30°$, $\theta_5 = 120°$ at the center frequency, ω_0 and $\theta_6 = 90°$ at the rejection frequency, ω_{rej}. The characteristic impedances of the stubs and TLs of the unit cell are determined by using the method described in (Sung, 2015). When Z_1 is selected as 100 Ω, the calculated impedances are Z_2 = 47 Ω, Z_3 = 86.1 Ω, Z_4 = 131.5 Ω, Z_5 = 107.9 Ω and Z_6 = 200 Ω. For 2.8-5 GHz and 6.3-7.6 GHz, $Y_a>0$ and $Y_c<0$; and for 5-5.4 GHz and 7.6-10.5 GHz, $Y_a<0$ and $Y_c>0$. Therefore, the RH regions in this distributed CRLH TL unit cell are 2.8-5 and 6.3-7.6 GHz and the LH regions are 5-5.4 and 7.6-10.5 GHz. Figure 3 shows the wide passband characteristic between ω_{sh1} and ω_{sh2} with a notched band at ω_{rej}. The frequency responses of the unit cell are shown in Fig. 4.

RESULTS AND DISCUSSION

A UWB bandpass filter with a notched band was implemented on a 0.6-mm-thick FR-4 substrate with a dielectric constant of 4.4 and a loss tangent of less than 0.02. Figure 5 shows the fabricated UWB bandpass filter. To achieve a narrow bandwidth, the characteristic impedance, Z_6 of the open-circuited stub in Fig. 1 becomes extremely high. This may be difficult to fabricate. A spur-line may be utilized to overcome this problem (Shaman and Hong, 2007). With the aid of an Electromagnetic (EM) simulator, the dimensions of the structure can be optimized to w_1 = 1.17 mm, w_2 = 0.3 mm, $w_3 = w_4 = w_5 = w_6$ = 0.2 mm, w_7 = 0.3 mm, g_1 = 0.2 mm, l_1 = 2.5 mm, l_2 = 1.19 mm, l_3 = 1.85 mm, l_4 = 4.57 mm, l_5 = 2.73 mm, l_6 = 2.28 mm, l_7 = 4.17 and l_8 = 7.4 mm. The size of the fabricated UWB BPF is 19.37×6.02 mm^2. The measurements are carried out using an Anritsu 37347C vector network analyzer. Figure 6a shows the simulated and measured amplitude



(a)



(b)

Fig. 6: Simulated and measured frequency responses of UWB BPF; (a): Wideband amplitude response; (b): Group delay

Table 1: Comparison of UWB bandpass filters

Reference	Song *et al*. (2012)	Cui *et al*. (2014)	Guan *et al*. (2014)	Zheng *et al*. (2014)	This study
Frequency (GHz)	2.60-11.10	3.1-10.6	3.20-10.60	3.10-10.60	2.80-10.50
Notched freq. (GHz)	5.70	7.9	5.25	5.80	5.75
# of layers	2.00	2.0	2.00	2.00	1.00
Max. IL (dB)	1.10	1.2	2.00	Not given	3.00
Min. IL (dB) at ω_{rej}	10.00	30.0	30.00	30.00	27.00
Filter size (mm^2)	8.5×7	13×7.5	28×18	27.10×14.16	19.40×6.00
Group delay variation (nsec)	0.24	Not given	0.49	Not given	0.37

responses of the fabricated filter; the responses show good agreement. The measured results have an insertion loss of less than 3 dB in a passband ranging from 2.8 to 10.5 GHz and a rejection of greater than 27 dB at 5.75 GHz. The simulated and measured group delays of the filter are shown in Fig. 6b. The measured group delay varies between 0.28 and 0.65 nsec with a maximum variation of 0.37 nsec over its entire passband. The fabricated UWB BPF is more compact than the example in Guan *et al*. (2014) and Zheng *et al*. (2014) and has a simpler structure compared with that of Song *et al*. (2012), Cui *et al*. (2014), Guan *et al*.

(2014) and Zheng *et al*. (2014), in which the UWB BPFs are implemented using two layers. Insertion losses in this study are relatively large because their substrates are FR-4s with a relatively large loss tangent. Table 1 shows the performance comparison of this study and previous works.

CONCLUSION

In this study, a novel UWB BPF with a notched band that adopts distributed CRLH TLs was designed, fabricated, measured and discussed. The unit cell of the CRLH TLs was theoretically analyzed to derive the dispersion characteristics and scattering parameters. This filter has a simple structure, compact size and good rejection performance. The measured results appear to agree with the simulation results.

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