Progress In Electromagnetics Research C, Vol. 22, 85–96, 2011

A NOVEL SMALL ULTRA-WIDEBAND BANDPASS FILTER INCLUDING NARROW NOTCHED BAND UTILIZING FOLDED-T-SHAPED STEPPED IMPEDANCE RESONATOR (SIR)

M. Mirzaee*

Department of Electrical and Electronics Engineering, Eslam Abad Branch, Islamic Azad university, Eslam Abad, Kermanshah, Iran

Abstract—A compact microstrip ultra-wideband (UWB) bandpass filter (BPF) including a narrow notched band within the UWB passband is proposed. The proposed filter is constructed by combination of two highly compact wideband bandpass filters (BPFs) with different physical dimensions which are designed on the basis of a folded-T-shaped stepped impedance resonator (SIR) and parallel-coupling feed structure. The wideband BPFs can be designed separately, and the design procedure is described. The narrow notched band with 3.8% 3 dB fractional bandwidth (FBW) from 5.15 to 5.35 GHz (IEEE 802.11a lower band) is created in order to eliminate interference from wireless local area network (WLAN) with the determined UWB passband. The center frequency and bandwidth of the notched band can be controlled by tuning the structural parameters. The full-wave EM simulated and measured results are in good agreement, showing that the proposed filter possesses good characteristics including wide passband, high selectivity, low insertion loss, large notch deep and sharp rejection.

1. INTRODUCTION

Recent studies in microwave filters demonstrate that many research efforts have been focused on designing ultra-wideband (UWB) bandpass filters (BPFs) due to increasing demand for UWB communication systems. These studies have risen considerably since the U.S. Federal Communications Commission (FCC) authorized the unlicensed use of the frequency band from 3.1 to 10.6 GHz for

Received 8 April 2011, Accepted 31 May 2011, Scheduled 15 June 2011

* Corresponding author: Milad Mirzaee (milad.mirzaee@gmail.com).

commercial purposes [1]. In addition, UWB microstrip filters as a key passive component have a preference for integration in low power and high-speed wireless communication systems. Due to the compact size, ease of fabrication, low cost and easy integration with other microwave circuits, planar filters have attracted attention both in industry and academia. Previously, several design approaches on the development of new UWB BPFs have been discussed in many references [2–11]. For more size reduction and improving filter performance, some of the filter configurations utilize stub-loaded multiple-mode resonator (MMR) [2, 3], composite right/left-handed transmission lines [4–6], defected ground structure (DGS) [7, 8], fractal technologies [9, 10], complementary split ring resonator [11]. Although most of these UWB BPFs are suitable for use in practical UWB systems, their applicability may be limited by existing narrowband radio signals such as wireless local area network (WLAN) that may interfere with the UWB system in the UWB frequency band of 3.1 to 10.6 GHz. Therefore, a communication system operating in the UWB frequency band requires BPF including narrow bandstop notches in order to eliminate interference from other services. UWB BPFs including notched band in the UWB passband were realized by using stepped impedance open-circuited series stubs in coplanar stripline technology [12], parasitic coupled line [13], and two pairs of stepped-impedance coupled open stubs implemented on the MMR [14]. Although compact size has been reported, the above realizations generate slow-rate transition since transmission zeros is not located near the operating passband. The conventional technique to improve microstrip BPFs performance at high frequency is defected ground structure (DGS) which is implemented by etching the slot in ground plane leading to an increase in effective inductance and capacitance of the microstrip transmission line. Combining double H-shaped slot and three pairs of tapered DGSs to achieve a small sized UWB BPF and a meander line slot to produce a narrow notched band in [15], two symmetrical open loop DGSs in [16], a hybrid microstrip coplanar waveguide (CPW) in [17], broadside-coupled microstrip-coplanar waveguide structure in [18], multi layer structure in [19] and [20] cause many disadvantages including design complexity, fabrication difficulty, cost increase and hard integration with other microwave circuits. Recently developed UWB BPF produces bandstop notch by using an embedded open-circuited stub [21]. However, the filter is still embarrassed by relatively large area and complex structure.

Due to large freedom of their geometries, capability of making more compact structure and tunable harmonic response property, stepped impedance resonators (SIRs) found many applications in wireless communication systems [22–26]. In this paper, the author aims at developing a novel compact notched band UWB BPF by combining two wideband bandpass filters with different physical dimensions which are designed on the basis of a folded-T-shaped stepped impedance resonator and parallel-coupling feed structure. The novel notched band UWB BPF has compact size, low passband insertion loss, sharp rejection, large notch deep and relatively wide stopband. Both proposed wideband and ultra-wideband BPFs are designed and fabricated on the Rogers RO4003 substrate with a relative dielectric constant of 3.38 and a thickness of 1.52 mm.

2. RESONANCE CHARACTERISTICS OF SIR

Figure 1 presents the evolution of folded-T-shaped stepped impedance resonator from conventional model stage by stage, which for more compactness the narrow section in conventional SIR is converted to two parts as in Figure 1(b) and then is folded back towards the wider section. As discussed in [14], based on transmission line theory, the equivalent circuit for the conventional open-circuited stepped impedance resonator shown in Figure 2 can be approximated as a series LC resonator. As indicated in Figure 2, the conventional

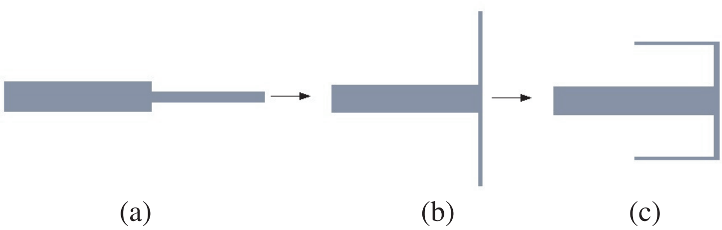

Figure 1. Evolution of folded-T-shaped SIR from conventional model.

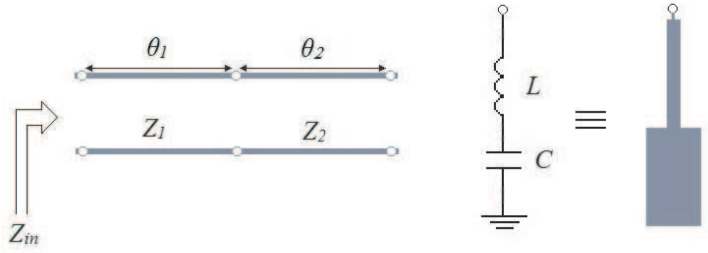

Figure 2. Equivalent circuit model of an open-circuited SIR.

open-circuited SIR is constructed by two sections with different characteristic impedances, the narrower line section with characteristic impedance Z_1 and electrical length θ_1 and wider line section with characteristic impedance Z_2 and electrical length θ_2.

The input impedance Z_{in} can be calculated by the following equation:

$$Z_{in} = jZ_1 \frac{Z_1 \tan\theta_1 \tan\theta_2 - Z_2}{Z_1 \tan\theta_1 + Z_2 \tan\theta_1} \tag{1}$$

Let Z_{in} to zero, the resonance condition can be derived by:

$$R_z - \tan\theta_1 \tan\theta_2 = 0 \tag{2}$$

where $R_z = Z_2/Z_1$ is the impedance ratio of the SIR. The fundamental and higher order resonant frequencies can be adjusted over a wide frequency range with tuning of the R_z and length ratio U defined as

$$U = \frac{\theta_2}{\theta_1 + \theta_2} \tag{3}$$

When $\theta_1 = \theta_2 \equiv \theta_0$, it can be obtained from (2)

$$\theta_1 = \theta_2 \equiv \theta_0 = \arctan\sqrt{R_z} \tag{4}$$

And the ratio of fundamental and second harmonic resonance frequencies f_0, f_{s1}, with corresponding electrical lengths θ_0 and θ_{s1} respectively, can be defined as [27, 28]

$$\frac{f_{s1}}{f_0} = \frac{\theta_{s1}}{\theta_0} = \frac{\pi - \theta_0}{\theta_0} = \frac{\pi}{\arctan\sqrt{R_z}} - 1 \tag{5}$$

This implies that by appropriately determining the impedance ratio R_z, it is possible to achieve two resonant frequencies with any desired ratio for applications such as dual-band filter. However, dependent on the choice of U and R_z, it is feasible to couple different resonant modes to obtain a wide passband. For instance, it was found that when considering that $f_0 = 4\,\text{GHz}$ and $f_{s1} = 5.8\,\text{GHz}$ with $R_z = 0.25$, the length ratio U can be explicitly determined as nearly 0.65 to achieve the desired wideband [25, 26].

3. COMPACT WIDEBAND BANDPASS FILTER WITH WIDE STOPBAND

Figure 3 indicates the configuration of the designed wideband BPF utilizing folded-T-shaped stepped impedance resonator with capability of resonating on fundamental and higher order resonant modes similar to conventional SIR. The proposed wideband BPF is constructed by two feeding lines coupled with the folded-T-shaped SIR, leading to the

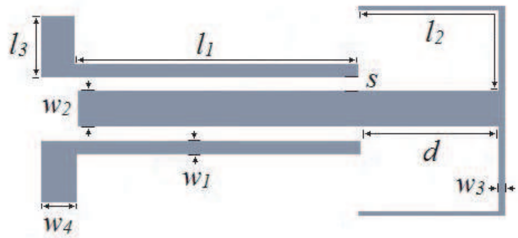

Figure 3. Schematic of designed wideband BPF.

strong coupling as well as providing additional transmission zeros in the upper and lower skirts of the passband, resulting in sharp roll-off. In order to achieve wideband wide stopband BPF, the initial physical parameters of the basic resonator can be obtained from design curves created for fundamental and higher resonant modes versus U as a function of R_z [25, 26]. Once U and R_z are determined, the high impedance segment can be realized by two identical lines which might be folded back for more compactness. The parameters of high impedance lines of the folded-T-shaped resonator are chosen: $L_2 = 7$ mm, $W_3 = 0.1$ mm. The resonant frequencies of the folded-T-shaped resonator depend on the low impedance line. As the length $L_1 + d$ increases, the resonant frequencies shift to the lower frequency. Hence, by properly tuning $L_1 + d$, the wideband BPF with any desired passband can be obtained if the folded-T-shaped SIR is properly fed with input-output parallel-coupling feed structure.

From Figure 4, by increasing the length $L_1 + d$ of the low impedance line from 14.8 to 20.8 mm with steps of 2 mm while W_2 remain 0.5 mm, the center frequency of the wide passband varies from 4.39 GHz to 3.53 GHz. In addition, it is possible to change 3 dB FWB of the passband at the desired center frequency by changing spacing S. For instance tuning the FBW at the center frequency of 3.5 GHz is interpreted in Figure 5. It can be seen apparently that by increasing S from 0.1 to 0.7 mm with steps of 0.2 mm, the FBW decreases slightly from 62.81% to 26.59%. To have desired frequency performance comparable with those of conventional ones, the parameters of the proposed wideband BPF are optimized by the EM-simulator ADS. The optimized dimensions have been tuned as $L_1 = 11.8$, $d = 5$, $L_2 = 7$, $L_3 = 1.05$, $W_1 = 0.25$, $W_2 = 0.5$, $W_3 = 0.1$, $W_4 = 0.8$ and $S = 0.17$ (all in millimeters). After analyzing the characteristics of the proposed filter, the highly compact wideband BPF is fabricated on Rogers RO4003, and its photograph is shown in Figure 7. The S-parameters measurements have been performed

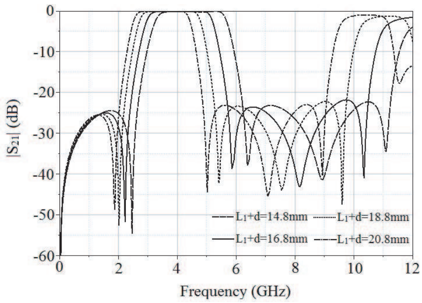

Figure 4. Simulated S_{21} of proposed wideband BPF as a function of $L_1 + d$.

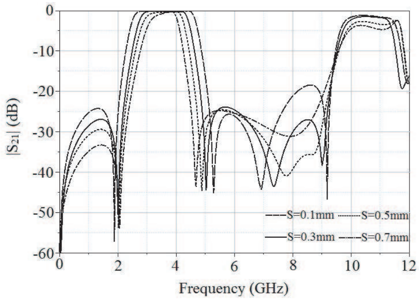

Figure 5. Simulated S_{21} of proposed wideband BPF as a function of S at the center frequency of 3.5 GHz.

using an Agilent 8722ES network analyzer. Figure 6 presents the EM simulated and measured results of the designed filter, which show a good agreement with each other. As seen from the results, the proposed filter provides wide passband from 2.91 to 5.22 GHz with 56.82% 3 dB fractional bandwidth. Four major transmissions zeros are located at 2.29, 5.88, 8.07 and 9.96 GHz with −55.86, −40.24, −42.09 and −53.37 dB attenuation levels, respectively, resulting in sharp skirt and deep upper stopband characteristics. The insertion loss is less than 0.26 dB and return loss higher than 15 dB in the passband. The upper stopband has a width of 5.28 GHz with attenuation level better than −20 dB, approximately around 64.59% of bandwidth that is improved around 44% and 15% in comparison with designs presented in [25] and [26], respectively, for the same bandwidth ratio. The actual size of the proposed wideband BPF structure is $17.9 \times 4.7\,\text{mm}^2$, thus size reduction around 82% and 90% is achieved in comparison with wideband bandpass filters reported in [25] and [26], respectively (with taking into consideration the length of their feedlines).

4. ULTRA-WIDEBAND BANDPASS FILTER INCLUDING NARROW NOTCHED BAND

By utilizing the proposed wideband BPF discussed in the previous section, an ultra-wideband bandpass filter with good performances and highly rejected notched band can be designed and simulated. The configuration of the designed notched band UWB filter is shown in Figure 8. To achieve very wide passband with bandstop notch characteristics, the proposed wideband BPFs with different physical

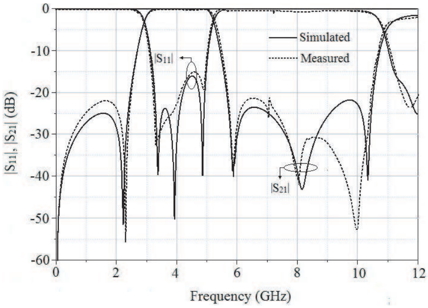

Figure 6. Simulated and measured results of wideband BPF.

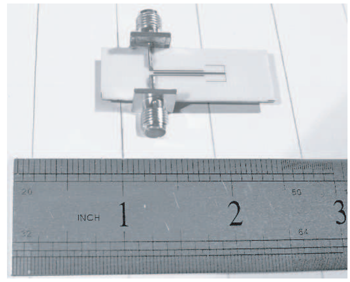

Figure 7. Photograph of fabricated wideband BPF.

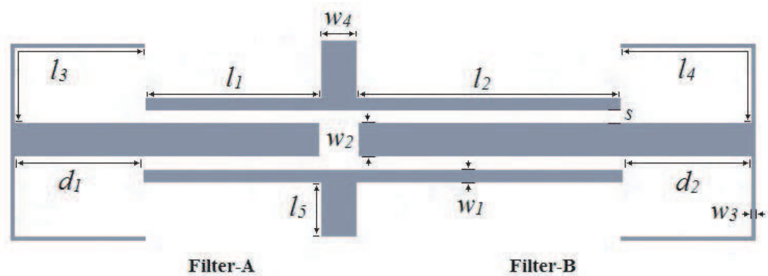

Figure 8. Schematic of designed notched band UWB BPF.

dimensions named as Filter-A and Filter-B are combined together. The simulated S_{21} for each wideband BPF is shown in Figure 9(a) individually and as a whole structure, hence, the mechanism of creating UWB passband with bandstop notch and transmission zeros at the lower and upper sides of passband edges can be discovered. By tuning structural parameters and spacing S, the notch response can be adjusted. It can be seen in Figure 9(b) that as the $L_1 + d_1$ length increases from 8.5 to 10 mm with steps of 0.5 mm while $L_2 + d_2$ and S remain 16.5 and 0.14 mm, respectively, the notch 3 dB bandwidth slightly increases from 0.74% to 12.52% and notch shifts to lower frequency with larger rejection level. However, from Figure 9(c) as the $L_2 + d_2$ length decreases from 17.5 to 16 mm with steps of 0.5 mm while $L_1 + d_1$ and S remain 9.2 and 0.14 mm, respectively, the notch 3 dB bandwidth slightly increases from 1.02% to 6.54%, and the notch shifts to higher frequency with larger rejection level. The major reason for this behavior is that by tuning $L_1 + d_1$ and $L_2 + d_2$, the resonant frequencies of the folded-T-shaped SIRs will change. The spacing S

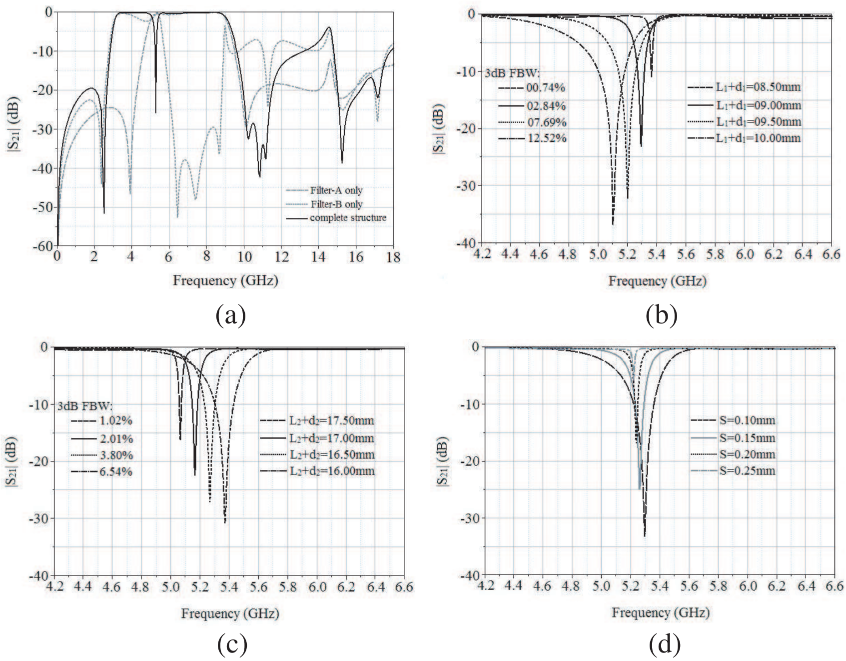

Figure 9. (a) Simulated S_{21} of Filter-A, Filter-B and whole structure. (b) Simulated results of rejection characteristics as a function of L_1+d_1. (c) Simulated results of rejection characteristics as a function of L_2+d_2. (d) Simulated results of rejection characteristics as a function of S.

has considerable influence on the bandwidth and the rejection level of the notch. Figure 9(d) depicts the simulated results of the rejection characteristics as a function of S. By increasing S, as a result of weak coupling, the notch bandwidth decreases, and the rejection level becomes lower. In order to evaluate frequency performance of the designed notched band UWB BPF, the filter is simulated by an EM-simulator ADS. The optimized dimensions are obtained: $L_1 = 6.2$, $d_1 = 3$, $L_2 = 12.5$, $d_2 = 3.95$, $L_3 = 5$, $L_4 = 4.65$, $L_5 = 1$, $W_1 = 0.15$, $W_2 = 0.4$, $W_3 = 0.1$, $W_4 = 0.8$ and $S = 0.14$ (all in millimeters). To validate the proposed design approach, the high performance notched band UWB BPF above is fabricated on Rogers RO4003 and measured using an Agilent 8722ES network analyzer. A photograph of the fabricated filter is shown in Figure 11. The EM simulated and measured results of the designed filter are presented in Figure 10, which show good agreement with each other. As seen from the results, the filter has wide passband from 3.01 to 9.27 GHz

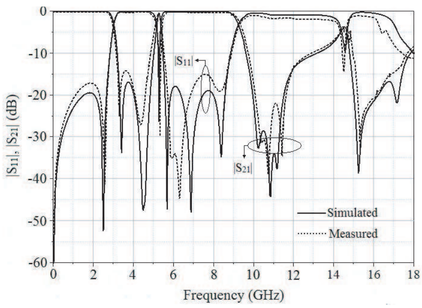

Figure 10. Simulated and measured results of notched band UWB BPF.

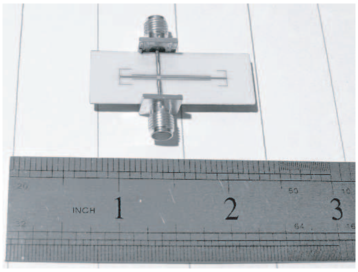

Figure 11. Photograph of fabricated notched band UWB BPF.

with 101.95% 3 dB FBW including narrow bandstop notch with 3.8% 3 dB FBW from 5.15 to 5.35 GHz and −29.63 dB attenuation level. The transmissions zeros are clearly observed near the UWB passband at 2.56 and 10.92 GHz with −41.10 and −38.12 dB attenuation levels, respectively, resulting in high selectivity and sharper slope response than those reported in [12] and [13]. The insertion loss is less than 0.37 dB, and return loss is higher than 14.18 dB in the passband. The actual size of the proposed structure is $26.65 \times 4.8\,\text{mm}^2$, thus, size reduction around 52% and 42% is achieved in comparison with notched band UWB filters reported in [12] and [13], respectively (with taking into consideration the length of their feedlines).

5. CONCLUSION

Utilizing folded-T-shape model of stepped-impedance resonator, a compact wideband bandpass filter has been developed and introduced. Combining the proposed wideband bandpass filters with different physical dimensions was used to corroborate ultra-wideband bandpass filter with notched band characteristics. The proposed filter realizes very wide passband with 101.95% 3 dB FBW including a narrow bandstop notch with 3.8% 3 dB FBW at the center frequency of 5.25 GHz with large deep in order to eliminate interference from wireless local area network (WLAN) with the determined UWB passband. Compared to the existing notched band filter designs in the literature the proposed filter has simple structure, compact size, high performance, and easy fabrication. These attractive features make the design suitable for employing in advanced UWB wireless communication systems.

ACKNOWLEDGMENT

The author would like to thank Mr. M. Akhlaghpasandi, Iran Telecommunication Research Center (ITRC) for his assistance in measurement.

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