An Ultra-Wideband Bandpass Filter With an Embedded Open-Circuited Stub Structure to Improve In-Band Performance

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***Abstract*—In this letter, we present a compact ultra-wideband bandpass filter (BPF) with a notch band in the BPF performance by using an embedded open-circuited stub structure. The filter mainly consists of conventional stepped impedance resonator (SIR) as the multiple-mode resonator and two enhanced coupled input/output lines. The bandwidth can be analyzed by using the image-parameter method to obtain the proper dimension of the coupled lines and verified by using electromagnetic (EM) simulation. The embedded open-circuited stub structure in the SIR is used to produce a narrow notched band at 5.8 GHz, which its frequency position and bandwidth can be tuned by its physical parameters. The measured 3 dB fractional bandwidth of 113.8% and narrow notched band with 25 dB rejection is achieved. Good agreement between the EM simulation and measurement is obtained.**

***Index Terms*—Bandpass filter (BPF), notched band, open-circuited stub, ultra-wideband (UWB).**

I. Introduction

In 2002, the U.S. Federal Communications Commission (FCC) authorized the unlicensed use of Ultra-Wideband (UWB, from 3.1 to 10.6 GHz) for a variety of applications, for instance indoor and hand-held systems [1]. Being a key component, a high performance UWB bandpass filter (BPF) is required. In recent years, several different topologies of UWB BPF have been reported [2]–[6]. UWB filters using multiple-mode resonator (MMR) have been widely studied [2]–[4]. The UWB performance was achieved by using tight coupled of I/O lines and conventional stepped impedance resonator (SIR) with an impedance ratio K larger than 1. However, a notched band is needed at 5.2 –5.8 GHz to avoid the interference from the existing wireless local area network (WLAN) band. Therefore, conventional or new UWB BPFs with a notched band were developed. For example, an UWB filter using MMR with a rejection band at 6.6 GHz by introducing two asymmetric stubs in the I/O coupled-line sections was demonstrated [7]. In [8], *Wong et al.* proposed the UWB filter using modified non-uniform resonator as the MMR. By using the same scheme of the two folded asymmetric stubs in the I/O coupled-line sections, a notched band was also achieved. In [9], *Yang et al.* proposed the small UWB filter with a notched band as well as a wide out-of-band by using the etched H-shaped slot and the defected ground structure (DGS). However, the use of the slots and DGSs etched in the ground plane might destroy the signal integrity issues for packaging.

In this letter, we propose an UWB BPF with the embedded open-circuited stub structure for achieving small circuit size and narrow notched band at 5.8 GHz at the same time. The filter consists of conventional stepped impedance resonator (SIR) as the MMR and two enhanced coupled I/O lines. We verify that the tight coupled I/O lines are necessary for introducing the UWB frequency response by using the image-parameter method and the electromagnetic (EM) simulation. With the embedded open-circuited stub structure in the MMR, the UWB response is still obtained and a desirable notched band is achieved. The theory and guideline for designing the geometric parameters of the proposed UWB BPF are presented in Section II. The UWB BPF is designed, fabricated and measured, showing a good agreement with the EM simulation.

II. Circuit Design

Fig. 1 shows the configuration of the proposed UWB BPF with the embedded open-circuited stub structure. The substrate used for simulation and fabrication in this study is RT/Duroid 6010 with a dielectric constant $(\varepsilon_{\mathrm{r}})$ of 10.2 and a thickness of 1.27 mm. It consists of a conventional SIR with the embedded open-circuited stub and two enhanced interdigital coupled I/O lines. Fig. 2 shows the equivalent transmission line model of the proposed UWB filter. The model is divided into two sections, interdigital couplers for the I/O lines for performing the tight coupling and a conventional SIR with the embedded open-circuited stub to have a notched band. At the first step of design procedure, the wide band characteristic can be understood from the frequency response of the I/O lines. The equivalent transmission line model of the coupled I/O lines can be further converted to the asymmetric coupled line [9], as shown in Fig. 3(a). In order to simplify the investigation, the impedance Z_3 and the length of the coupled line are chosen to be 111 Ω $(W_1 = 0.1\ \mathrm{mm})$ and 4.25mm (quarter-wavelength at 6.8 GHz and $\theta_3 = 90^\circ$), respectively. As presented in [9], the characteristic modes for an asymmetric coupled line are named as the "c" mode and "p" mode. The image impedance Z_i can be derived from [10]

$$Z_i = \frac{\sqrt{\left(Z_{0e}^j - Z_{0o}^j\right)^2 - \left(Z_{0e}^j + Z_{0o}^j\right)^2 \cos^2\theta_3}}{2\sin\theta_3} \tag{1}$$

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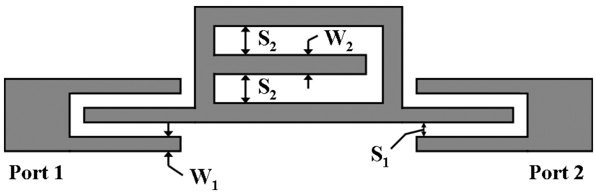

Fig. 1. Configuration of the UWB BPF with the embedded open-circuited stub structure.

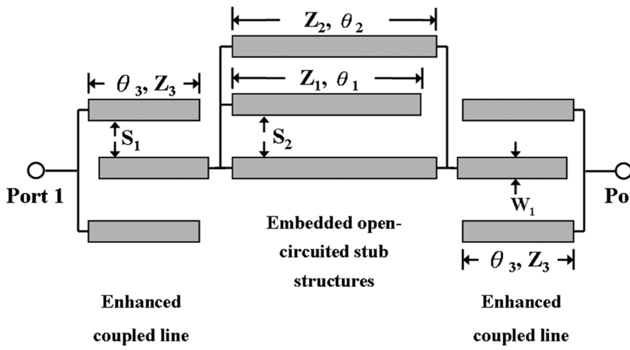

Fig. 2. Equivalent transmission line model of the proposed UWB filter.

where index j indicates c- and p-mode and the Z_{0e} and Z_{0o} indicate the characteristic impedance with even- and odd mode for a general coupled line. When Z_i is equal to $\pm j\infty$ and $Re(Z_i)$ is equal to 0, a bandstop edge is introduced [10]. We then define a normalized bandwidth (NBW) of image impedance by subtracting right bandstop edge and left bandstop edge[6]. It is found that when S_1 varies from 0.1, 0.3 to 0.5 mm, corresponding to (Z_{0e}, Z_{0o}) of (168 Ω, 51 Ω), (148 Ω, 69 Ω) and (136 Ω, 78 Ω) for c-mode and (123 Ω, 37 Ω), (114 Ω, 53 Ω) and (108 Ω, 62 Ω) for p-mode, the estimated normalized bandwidth (NBW) of 73%, 49% and 37% can be well achieved, as shown in Fig. 3(b). In a previous work, it is found that the NBW calculated from the image parameter has corresponding relations with the 1.5 dB FBW and 3 dB FBW estimated from the EM simulation [6]. The relation between the NBW and 3 dB FBW are listed in the Table I. S_1 of 0.1mm is chosen to have the satisfied FBW in this study.

At the second step of design procedure, the narrow notched band inside the UWB filter performance can be introduced by the embedded open-circuited stub structure in the MMR. As referenced in most papers regarding to the MMR [2]–[4], the MMR with an impedance ratio K of 2.3 introduces three resonant peaks (f_0, f_{s1} and f_{s2}) at around 4.2, 6.6 and 9.2 GHz. It is found that even with the embedded open-circuited stub structure, the UWB response is still obtained, and a desirable notched band is achieved. Fig. 4(a) shows the equivalent transmission line model of the embedded open-circuited stub structure in the MMR. The ABCD matrix of the circuit is given as

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cos\theta_2 & j\frac{Z_2}{2}\sin\theta_2 \\ j\left(Y_1\cos\theta_2\tan\theta_1 + \frac{2\sin\theta_2}{Z_2}\right) & -\frac{Y_1 Z_2}{2}\tan\theta_1\sin\theta_2 + \cos\theta_2 \end{bmatrix}. \quad (2)$$

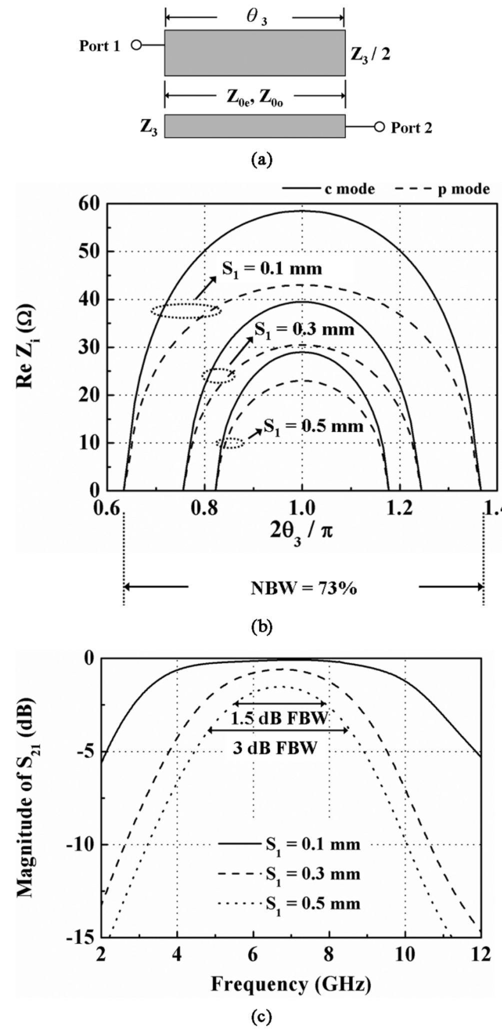

Fig. 3. (a) Transmission line model, (b) the real part of the image impedance with c and p mode and (c) EM simulated frequency response of the asymmetric coupled line under different coupling gap S_1.

TABLE I
RELATION BETWEEN THE NBW AND 3DB FBW FOR THE ASYMMETRIC COUPLED LINES

	S_1 = 0.1 mm	S_1 = 0.3 mm	S_1 = 0.5 mm
NBW (%)	73	49	37
1.5dB FBW by EM simu. (%)	77	54	43
3dB FBW by EM simu. (%)	113	82.5	61
3dB FBW / NBW	1.54	1.68	1.65

Therefore, the simplified expression of the image impedance for this structure is

$$Z_i = \sqrt{\frac{AB}{CD}} = \sqrt{\frac{\frac{Z_2}{2}\sin\theta_2\cos\theta_2}{\left(Y_1\cos\theta_2\tan\theta_1 + \frac{2\sin\theta_2}{Z_2}\right)\left(\cos\theta_2 - \frac{Y_1 Z_2}{2}\tan\theta_1\sin\theta_2\right)}}. \quad (3)$$

It is found that the frequency of the notched band can be tuned by the length L (i.e θ_1) and the bandwidth of the notched band can be controlled by tuning the different width (i.e impedance Z_1) of the embedded open-circuited stub. Fig. 4(b) and (c) show the simulated frequency response of the proposed BPF with tuning L and W_2, respectively. It is clearly observed that with

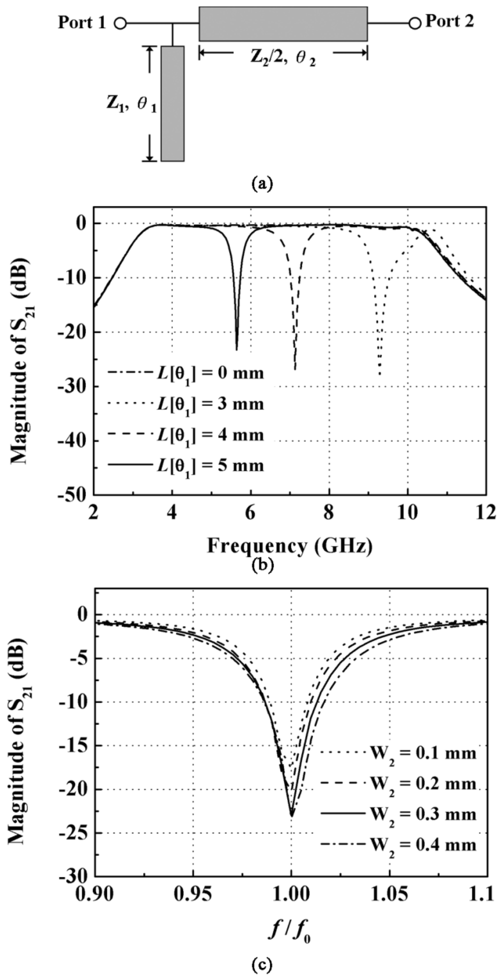

Fig. 4. (a) Equivalent circuit model of the embedded open-circuited stub in the MMR, and simulated frequency response with tuning (a) the physical length L and (b) the width W_2 of the embedded open-circuited stub.

increasing L, the notched band is shifted to lower frequency and with increasing W_2, the bandwidth of the notched band slightly increases. After choosing L of 5 mm ($\theta_1 = 150^\circ$) and W_2 of 0.3 mm ($Z_1 = 70\ \Omega$), the 10 dB notched bandwidth of around 5% at the center frequency 5.8 GHz can be achieved and thus the spacing S_2 and impedance Z_2 are determined as 0.1 mm and 90 Ω, respectively.

III. Results

Using the optimized structural parameters, the designed BPF was fabricated and measured on an HP8510C Network Analyzer. Fig. 5 shows the measured frequency responses compared with the EM simulation as well as the FCC mask. The measured results have a 3 dB FBW of 113.8% and a notched band at 5.8 GHz with 10 dB rejection bandwidth of around 5%. For the lower and higher passbands, the $|S_{11}|$ is larger than 17 and 25 dB, and the measured $|S_{21}|$ is less than 0.5 and 2 dB, respectively. The in-band isolation is 25 dB. Moreover, the measured group delays within the lower and higher band are both less than 0.5 ns. The measured results are slightly different than the simulated results in the higher passband. It can be considered as the variation of the material property. The size of the fabricated BPF is $7.3 \times 1.08\ \mathrm{mm}^2$, i.e., approximately 0.4 λ_g by 0.06 λ_g, where

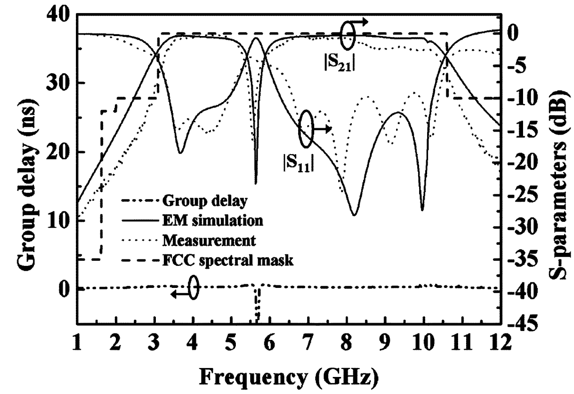

Fig. 5. Photograph and measured results of the fabricated BPF. $S_1 = S_2 = W_1 = 0.1$ mm and $W_2 = 0.3$ mm.

λ_g is the guided wavelength at the center frequency (6.8 GHz). The superior features indicate that the BPF has a potential to be utilized in the modern ultra-wideband wireless communication system [11], [12].

IV. Conclusion

In this letter, a compact UWB BPF with a notch band by using the embedded open-circuited stub has been presented. It is also verified that the tight coupled I/O lines are necessary for introducing the UWB frequency response by using the image-parameter method and the EM simulation. With the embedded open-circuited stub structure in the MMR, the UWB response is still obtained and a desirable notched band at 5.8 GHz is achieved.

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