Tri-band Microstrip Bandpass Filter Using Dual-Mode Stepped-Impedance Resonator

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This letter presents a compact dual-mode tri-band bandpass filter by using a short-circuited stub-loaded stepped-impedance resonator (SIR) and a short-circuited stub-loaded uniform impedance resonator. Also, a hairpin SIR geometry is introduced to miniaturize the size of this filter while maintaining excellent performance. The use of a short-circuited stub at the central point of the hairpin SIR can generate two resonant modes in two passbands. Its equivalent circuit structure is analyzed by using the even-odd mode theory. For demonstration purposes, a tri-band filter for the applications of the Global Positioning System at 1.57 GHz, Worldwide Interoperability for Microwave Access at 3.5 GHz, and wireless local area networks at 5.2 GHz is designed, fabricated, and measured.

Keywords: Stepped-impedance resonator (SIR), bandpass filter, tri-band, dual-mode, even-odd mode theory.

I. Introduction

With the increasing demand for tri-band applications in modern wireless systems, such as the global systems for the Global Positioning System (GPS) at 1.57 GHz, Worldwide Interoperability for Microwave Access at 3.5 GHz, and wireless local area networks (WLANs) at 2.4/5.2 GHz, research on innovative designs of tri-band filters has become very popular. In [1], configurations of composite split-ring resonators are used to design a tri-band filter. The advantage of this filter is the ability to produce three passbands separated by transmission zeros. In [2], a tri-band bandpass filter (BPF) using three pairs of degenerate modes in a ring resonator was proposed. Recently, the square-ring-loaded resonator was proven in the design of a tri-band filter [3]. The square-ring short-stub-loaded resonator has been introduced for the design of a tri-band filter [4]. The tri-band BPFs can also be constructed using several stepped-impedance resonators (SIRs), as shown in [5]-[7]. In this letter, the proposed dual-mode hairpin SIR is a modified version of the conventional folded SIR. In [8], [9], the short-stub-loaded SIR is used to design dual-mode BPFs with wide stopbands. A dual-band dual-mode BPF using a single SIR with one and two short stubs loaded, was proposed in [10], [11], respectively.

In this work, a compact dual-mode tri-band BPF for wireless communication applications is proposed by using a short-circuited stub-loaded SIR and a short-circuited stub-loaded uniform impedance resonator. Even-odd mode theory is applied to explain the dual-mode characteristics and equivalent circuits of the proposed hairpin SIR. For demonstration purposes, a tri-band BPF is designed, fabricated, and measured.

II. Analysis of Proposed Dual-Mode SIR

A layout of the proposed dual-mode dual-band hairpin SIR with two feed lines is shown in Fig. 1, which is denoted by its lengths (L_1, L_2) and widths (w_1, w_2). Furthermore, two modes of this SIR can be excited by adding a short-circuited stub with length L_3 and width w_3 at the central plane to the SIR. Since the proposed resonator has a symmetrical structure, the even-odd mode theory is adopted to analyze its equivalent circuit structure. Its corresponding odd- and even-mode equivalent circuits are given in Fig. 2. Here, θ_1, θ_2, and θ_3 are electrical
lengths of the three sections with the lengths $L_1$, $L_2$, and $L_3$, respectively, and $Y_1$, $Y_2$, and $Y_3$ are the characteristic admittances of the widths $w_1$, $w_2$, and $w_3/2$. For simplicity, $Y_3$ is set to be equal to $Y_2$. Ignoring the influences of a step discontinuity, the input admittance $Y_{\text{in-even}}$ of the even-mode SIR, shown in Fig. 2(a), is expressed as

$$Y_{\text{in-even}} = -jY_1 - Y_2 \tan \theta_1 \tan(\theta_1 + \theta_2) - Y_3 \tan \theta_1 \tan(\theta_1 + \theta_2) \tan(\theta_1 + \theta_3).$$

Similarly, the input admittance $Y_{\text{in-odd}}$ of the odd-mode SIR in Fig. 2(b) can be extracted as

$$Y_{\text{in-odd}} = -jY_1 Y_2 - Y_1 \tan \theta_1 \tan \theta_2 - Y_2 \tan \theta_1 \tan \theta_2 \tan \theta_3.$$  

From the resonance condition $Y_{\text{in-odd}} = 0$ and $Y_{\text{in-even}} = 0$, the resonant frequencies can be expressed as

$$R_z - \tan \theta_1 \tan \theta_2 = 0, \quad \text{(at } f = f_{\text{odd}}\text{)},$$

$$R_z - \tan \theta_1 \tan(\theta_1 + \theta_2) = 0, \quad \text{(at } f = f_{\text{even}}\text{)},$$

where $f_{\text{odd}}$ and $f_{\text{even}}$ are the odd- and even-mode resonant frequencies of the proposed SIR, respectively. $R_z = Y_2/Y_1$ is the admittance ratio.

According to (3) and (4), the resonant frequencies of the proposed SIR can be controlled by electrical lengths $\theta_1$, $\theta_2$, and $\theta_3$ and admittance ratio $R_z$. Also, from (3), the resonant frequencies of odd-mode resonant frequencies are decided by $\theta_1$, $\theta_2$, and $R_z$. Thus, by properly choosing the parameters $\theta_1$, $\theta_2$, and admittance ratio $R_z$, the odd-mode resonant frequency $f_{\text{odd}}$ is proximately allocated in a certain passband. Then, we can adjust the even-mode resonant frequency $f_{\text{even}}$ by simply varying the parameter $\theta_3$ to realize a dual-mode resonator, according to (4).

From Fig. 2, the fundamental odd- and even-mode resonant frequencies, $f_{\text{odd}}$ and $f_{\text{even}}$, of the proposed SIR in the first passband can be approximately estimated as

$$f_{\text{even}} = \frac{c}{4(L_1 + L_2 + L_3)\sqrt{\varepsilon_{\text{eff}}}},$$

$$f_{\text{odd}} = \frac{c}{4(L_1 + L_2)\sqrt{\varepsilon_{\text{eff}}}},$$

where $c$ is the light speed in free space, $\varepsilon_{\text{eff}} = \varepsilon_r + \frac{1}{2} + \frac{1}{2}[(1 + \frac{2 \varepsilon_r - 1}{\varepsilon_r})^{1/2} + 0.04(1 - \frac{\varepsilon_r}{\varepsilon_r})]$, and $\varepsilon_r$ and $h$ denote the relative dielectric constant and thickness of the substrate, respectively; $\varepsilon_r$ can simply be estimated as $\varepsilon_r = \frac{\varepsilon_r}{\varepsilon_r}$. After the fundamental resonant frequency of this dual-mode SIR is designed to operate at the first passband, the first harmonic frequency can be designed to operate at the second passband. This resonant frequency can be easily tuned by the admittance ratio $R_z$ and produces two odd- and even-mode resonant frequencies, $f_{\text{odd}}$ and $f_{\text{even}}$, by this short-circuited stub.

To verify the theoretical analysis, a dual-mode dual-band resonator filter is designed using a full-wave electromagnetic simulator, Ansys HFSS 10. The first and the second passbands are set to a GPS band at 1.57 GHz and WLAN band at 5.2 GHz, respectively. The dimension parameters of this dual-band filter are optimized as follows: $w_1 = 1.1$ mm, $L_1 = 7.7$ mm,
It can be seen that the length and bandwidth of the passband can be adjusted by changing the stub length of the short-circuited stub. Responses of the filter with respect to a different stub length, such as 0.8 mm, can be obtained. A substrate with a relative dielectric constant of 4.5 and a thickness of 0.8 mm is used. The guided wavelength at the center frequency of the third passband is equal to the half-wavelength of the open loop Resonator 2. As discussed in section II, a pair of odd- and even-mode resonant frequencies can be excited and tuned by varying the length of the short-circuited stub. Two resonant frequencies at the third passband are given by

\[ f_{\text{odd}} = \frac{c}{4L_4\sqrt{\varepsilon_{\text{eff}}}} \]

\[ f_{\text{even}} = \frac{c}{4(L_4 + L_5)\sqrt{\varepsilon_{\text{eff}}}} \]

For demonstration purposes, a tri-band BPF respectively operating at 1.57 GHz, 3.5 GHz, and 5.2 GHz for GPS, WiMAX, and WLAN applications is designed. Following the aforementioned design method, the dimension parameters of this tri-band filter are optimized as follows: \( w_1 = 1.1 \, \text{mm}, \quad L_1 = 7.7 \, \text{mm}, \quad w_2 = 0.5 \, \text{mm}, \quad L_2 = 16.26 \, \text{mm}, \quad w_3 = 0.8 \, \text{mm}, \quad g_1 = 11.6 \, \text{mm}, \quad H_1 = 4.33 \, \text{mm}. \) The overall size of this filter is 15.2 mm \( \times \) 12.6 mm. The return losses within the two passbands are below -19.2 dB. For this study, a substrate with a relative dielectric constant of 4.5 and a thickness of 0.8 mm is used.

To check the effect of the short-circuited stub on the dual-mode characteristics, Fig. 4 shows the simulated frequency responses of the filter with respect to a different stub length, \( L_3 \). It can be seen that \( f_{\text{odd}} \) and \( f_{\text{even}} \) have a slight change while \( f_{\text{odd}} \) and \( f_{\text{even}} \) have an effective shift when tuning \( L_3 \). Moreover, the bandwidth of the passband can be adjusted by changing the length \( L_3 \) of the short-circuited stub.

III. Tri-band Filter Design

A layout of the designed tri-band BPF is shown in Fig. 5. It is a symmetrical structure and consists of two sets of resonators, Resonator 1 and Resonator 2. Resonator 1 is the proposed dual-mode dual-band hairpin SIR and is designed to operate at the first and second passband frequencies, \( f_1 \) and \( f_2 \). Resonator 2 is a short-circuited stub-loaded resonator and is used to generate the third passband at \( f_3 \).

Resonator 2 in Fig. 5 is a dual-mode resonator with a short-circuited stub perturbation at the symmetrical plane. For a given center frequency of the third passband, it is equal to the half-wavelength of the open loop Resonator 2. As discussed in the aforementioned design method, the dimension parameters of this tri-band filter are optimized as follows: \( w_1 = 1.1 \, \text{mm}, \quad L_1 = 7.7 \, \text{mm}, \quad w_2 = 0.5 \, \text{mm}, \quad L_2 = 16.26 \, \text{mm}, \quad w_3 = 0.8 \, \text{mm}, \quad g_1 = 11.6 \, \text{mm}, \quad H_1 = 4.33 \, \text{mm}. \) The overall size of this filter is 15.2 mm \( \times \) 12.6 mm.

In Fig. 6, measured and simulated results are shown. The measured 3-dB bandwidths for the three passbands centered at 1.57 GHz, 3.5 GHz, and 5.2 GHz are found to be 1.52 GHz to 1.62 GHz (6.37%), 4.8 GHz to 5.9 GHz (5.96%), and 4.8 GHz to 5.9 GHz (6.37%), respectively. The measured minimum insertion losses including the loss from SMA connectors are 0.99 dB, 1.01 dB, and 1.2 dB, while the return losses are better than 22.4 dB, 18.26 dB, and 15.6 dB, respectively. In addition, the proposed tri-band BPF can generate several transmission zeros on both sides of the passbands, which significantly improves the skirt selectivity. Six transmission zeros are created at 1.32 GHz, 1.93 GHz, 2.9 GHz, 4.23 GHz, 4.95 GHz, and 5.69 GHz. Because of the main path signal counteraction, three transmission zeros can be created near each passband [12], [13].
Owing to the fact that even-mode frequencies ($f_{\text{even1}}$, $f_{\text{even2}}$, and $f_{\text{even3}}$) are lower than the odd-mode ones ($f_{\text{odd1}}$, $f_{\text{odd2}}$, and $f_{\text{odd3}}$), shown in Fig. 7, $T_{z1}$, $T_{z3}$, and $T_{z5}$ would be located in the lower stopbands, respectively. The other three transmission zeros $T_{z2}$, $T_{z4}$, and $T_{z6}$ in the upper stopbands are excited by the short-stub perturbation [14].

IV. Conclusion

A compact tri-band BPF was presented in this letter. A new dual-mode dual-band hairpin SIR filter with a short-circuited stub was proposed and analyzed. Its excellent resonant characteristics and bandpass performances were studied and explained by using even-odd mode theory. This filter is particularly suitable for multiband and multiservice applications in mobile communication systems.

References