Design of a switchable microstrip bandstop filter with signal/dual stopbands

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Abstract

A switchable bandstop filter is proposed herein. In order to achieve switchability between a single ultra-wide stopband and dual wide stopbands, a complex process of coupling synthesis is not necessarily required. By setting two diodes at the input and output port separately, this bandstop filter can be switched between single and dual stopbands. An exemplary bandstop filter with central frequency at 2 GHz is fabricated on Rogers RO4003C, a substrate with a thickness of 0.813 mm and an area occupying 29.3 × 29.7 mm. Agreement between the theoretical and measured results can validate the proposed circuit.

1 | INTRODUCTION

In recent years, various wireless communication systems, such as mobile multimedia communication, near-body wireless healthcare, and wireless surveillance, have attracted research into applications with multi-bands. Therefore, communication systems with reconfigurability for new frequency bands are also essential. Tuneable filters have the potential to reduce the complexity and linearity requirements of wideband receivers.

Varactors are usually used for tuneable bandpass filters with constant bandwidths, bandwidth controlling, wide tuning range, or enhanced stopband performance [1–11]. In order to realise more precise tuning, MEMS with a high Q factor can be adopted [12, 13]. By including a PIN diode, filters with reconfigurability can be implemented [14–16]. Moreover, varactors can be utilised for both bandpass and bandstop filter [17, 18].

Like bandpass filters, bandstop filters also play important roles in front-end wireless communication systems. Bandstop filters have become very important due to emerging multi-standard systems. In multi-standard transceivers, an interfered frequency band can be switched to another frequency band by adopting tuneable bandstop filters. Moreover, for a high interference environment, bandstop filters are used to eliminate highly interfered power close to desired signals. In addition, circuit size miniaturisation is also demanded.

By using a microstrip transmission line loaded with L- and T-shaped resonators, a wide bandstop filter can be developed [19]. It is also important for designing absorptive bandstop filters [20], dual stopbands bandstop filters [21], and bandstop filters with high attenuation in the stopband [22].

Herein, a single ultra-wide stopband and dual wide stopbands based on signal-interference techniques are integrated in one bandstop filter, as shown in Figure 1, where two types of stopbands can be switched by changing two diodes' voltage at the input/output port. Moreover, 90° is adopted for electrical length $\theta_1$ of this proposed filter. Thus, reconfigurability of the proposed bandstop filter has been realised in this circuit.

In [23], two transmission paths with a half-wavelength open stub and two open-coupled lines shown in Figure 2 are used to realise two wide stopbands, whose performance is similar as our proposed filter operated in “off” state. Moreover,
state can be derived as in the following, and \(Z_0\) is port impedance at the input/output port.

### 2.1 Circuit in the “on” state

Input admittance \(Y_{on}^e\) of the even-mode equivalent circuit shown in Figure 3(a) is

\[
Y_{on}^e = Y_{on2}^e + Y_{on3}^e + Y_{on4}^e
\]

where

\[
Y_{on2}^e = Y_2 Y_{on1}^e + jY_2 \tan \theta_1
\]

\[
Y_{on1}^e = jY_1 \tan \theta_1
\]

\[
Y_{on3}^e = j \omega C_t \tan \theta_2 - Y_3\]

\[
Y_{on4}^e = Y_3 Y_{on3}^e + jY_3 \tan \theta_1
\]

\[
Z_{on3}^e = \frac{1}{Y_{on3}^e}
\]

\[
= j \left[ \frac{Z_e + Z_o \tan \theta_1 - 4Z_e Z_o \csc 2 \theta_1}{2} \right]
\]

Moreover, input admittance \(Y_{on}^o\) of the odd-mode equivalent circuit shown in Figure 3(b) is

\[
Y_{on}^o = Y_{on1}^o + Y_{on3}^o + Y_{on5}^o
\]

where

\[
Y_{on1}^o = -jY_2 \cot \theta_1
\]

\[
Y_{on3}^o = j \omega C_t \tan \theta_2 - Y_4\]

\[
Y_{on5}^o = Y_3 Y_{on2}^o + jY_3 \tan \theta_1
\]

\[
Z_{on2}^o = \frac{1}{Y_{on2}^o} = -\frac{2Z_e Z_o}{Z_e + Z_o} \cot \theta_1
\]

Reflection coefficients \(\Gamma_{on}^e\) and \(\Gamma_{on}^o\) of the bandstop filter in the “on” state can be then obtained as
Therefore, $S$-parameters of the bandstop filter in the “on” state can be derived as

$$S_{11}^{on} = S_{22}^{on} = \frac{\Gamma_{on}^c + \Gamma_{on}^o}{2} \quad (5)$$

$$S_{12}^{on} = S_{21}^{on} = \frac{\Gamma_{on}^c - \Gamma_{on}^o}{2} \quad (6)$$

Consequently, seven transmission zeros ($f_{z1}, f_{z2}, f_{z3}, f_{z4}, f_{z5}, f_{z6}, f_{z7}$) within the stopband, as indicated in Figure 3(c), can be obtained by setting $S_{12}^{on} = 0$, $\theta_1 = 90^\circ$, and $\theta_2 = 45^\circ$.

$$f_{z1} = \frac{4f_0}{\pi} \cdot \tan^{-1} \left( \frac{4B + 16\sqrt{2}B^2}{\sqrt{4B(C + \sqrt{C^2 - 1024B^4})}} \right) \quad (7)$$

$$f_{z2} = \frac{4f_0}{\pi} \cdot \tan^{-1} \sqrt{\frac{2Z_1}{Z_2}} \quad (8)$$

$$f_{z3} = \frac{4f_0}{\pi} \cdot \tan^{-1} \left( \frac{2\sqrt{ZZ_0}}{\sqrt{(Z_e + Z_o)(2Z_1 + Z_e + Z_o)} + \sqrt{(Z_e - Z_o)^2 + 2Z_3(Z_e + Z_o)}} \right) \quad (9)$$

$$f_{z4} = f_0 \quad (10)$$

$$f_{z5} = \frac{4f_0}{\pi} \cdot \tan^{-1} \left( \frac{2\sqrt{ZZ_0}}{\sqrt{(Z_e + Z_o)(2Z_3 + Z_e + Z_o)} - \sqrt{(Z_e - Z_o)^2 + 2Z_3(Z_e + Z_o)}} \right) \quad (11)$$

$$f_{z6} = 2f_0 \left( 1 - \frac{2}{\pi} \cdot \tan^{-1} \sqrt{\frac{2Z_1}{Z_2}} \right) \quad (12)$$

$$f_{z7} = 2f_0 \left( 1 - \frac{2}{\pi} \cdot \tan^{-1} \left( \frac{4B + 16\sqrt{2}B^2}{\sqrt{4B(C + \sqrt{C^2 - 1024B^4})}} \right) \right) \quad (13)$$

where

$$A = 3(Z_e + Z_o)^2 \quad (14)$$

$$B = Z_e Z_o \quad (15)$$

**Figure 3** Equivalent circuits of the bandstop filter in the “on” state:
(a) even mode; (b) odd mode; (c) theoretical responses

\[
\Gamma_{on}^c = \frac{Y_{on} - Y_{on}^c}{Y_{on} + Y_{on}^c} \quad (3) \\
\Gamma_{on}^o = \frac{Y_{on} - Y_{on}^o}{Y_{on} + Y_{on}^o} \quad (4)
\]
\[ C = 27Z_e^4 + 108Z_e^3Z_o + 97Z_e^2Z_o^2 + 108Z_eZ_o^3 + 27Z_e^4 \]  

(16)

### 2.2 Circuit in the “off” state

Input admittance \( Y_{\text{off}}^e \) of the even-mode equivalent circuit shown in Figure 4(a) is

\[ Y_{\text{off}}^e = Y_{\text{off}2}^e + Y_{\text{off}4}^e \]  

(17)

where

\[ Y_{\text{off}2}^e = Y_{\text{off}1}^e \frac{Y_2 \tan \theta_1}{Y_2 + jY_{\text{off}1}^e \tan \theta_1} \]  

(17a)

\[ Y_{\text{off}1}^e = j\frac{Y_1 \tan \theta_1}{2} \]  

(17b)

\[ Y_{\text{off}4}^e = Y_3^e \frac{Y_{\text{off}3}^e + jY_3 \tan \theta_1}{Y_3 + jY_{\text{off}3}^e \tan \theta_1} \]  

(17c)

\[ Z_{\text{off}3}^e = \frac{1}{Y_{\text{off}3}^e} \]  

\[ = j \left[ \frac{Z_e + Z_o}{2} \tan \theta_1 - \frac{4Z_eZ_o}{Z_e + Z_o} \csc 2\theta_1 \right] \]  

(17d)

Moreover, input admittance \( Y_{\text{off}}^o \) of the odd-mode equivalent circuit shown in Figure 4(b) is

\[ Y_{\text{off}}^o = Y_{\text{off}1}^o + Y_{\text{off}3}^o \]  

(18)

where

\[ Y_{\text{off}1}^o = -jY_2 \cot \theta_1 \]  

(18a)

\[ Y_{\text{off}3}^o = Y_3^o \frac{Y_{\text{off}2}^o + jY_3 \tan \theta_1}{Y_3 + jY_{\text{off}2}^o \tan \theta_1} \]  

(18b)

\[ Z_{\text{off}2}^o = \frac{1}{Y_{\text{off}2}^o} = -j \frac{2Z_eZ_o}{Z_e + Z_o} \cot \theta_1 \]  

(18c)

Reflection coefficients \( \Gamma_{\text{off}}^e \) and \( \Gamma_{\text{off}}^o \) of the bandstop filter in the “off” state can be then obtained as

\[ \Gamma_{\text{off}}^e = \frac{Y_0 - Y_{\text{off}}^e}{Y_0 + Y_{\text{off}}^e} \]  

(19)

\[ \Gamma_{\text{off}}^o = \frac{Y_0 - Y_{\text{off}}^o}{Y_0 + Y_{\text{off}}^o} \]  

(20)

**FIGURE 4** Equivalent circuits of the bandstop filter in the “off” state: (a) even mode; (b) odd mode; (c) theoretical responses
Therefore, S-parameters of the bandstop filter in the “off” state can be derived as

\[
S_{11}^{\text{off}} = S_{22}^{\text{off}} = \frac{\Gamma_{\text{off}}^e + \Gamma_{\text{off}}^o}{2}
\]

(21)

\[
S_{12}^{\text{off}} = S_{21}^{\text{off}} = \frac{\Gamma_{\text{off}}^e - \Gamma_{\text{off}}^o}{2}
\]

(22)

By setting \(S_{12}^{\text{off}} = 0\) and \(\theta_1 = 90^\circ\), six transmission zeros \(f_{z1}, f_{z2}, f_{z3}, f_{z5}, f_{z6}, f_{z7}\) (same as those in the “on” state) within two stopbands as indicated in Figure 4(c) can be obtained.

### 3 | CHARACTERISTICS OF THE PROPOSED SWITCHABLE BANDSTOP FILTER

In order to tune attenuation within the stopband, it is necessary to make transmission zeros \(f_{z2}\) and \(f_{z6}\) close to \(f_{z1}\) and \(f_{z7}\), respectively. With the proposed bandstop filter in the “on” state, Figure 5 shows that the greater the attenuation within the stopband is, the smaller \(C_s\) is. Moreover, it is not easy to implement the proposed filter with printed circuit board (PCB) technology due to a great value of \(Z_4\) being required. Here, impedance \(Z_4\) in the shorted stub is used to provide the required inductance to compensate the reactance of \(C_s\) at the central frequency, thus generating a transmission zero.

According to Figure 6, a smaller \(Z_1\) will make a higher attenuation level within the stopband with the proposed bandstop filter in both the “on” and “off” states. Moreover, according to Figure 7, a greater \(Z_3\) will result in a higher attenuation level within the stopband with the proposed bandstop filter in both the “on” and “off” states. Furthermore, a smaller \(Z_5\) will make a higher attenuation level within the stopband with the proposed bandstop filter in both the “on” and “off” states shown in Figure 8. However, there will be narrower bandwidths of dual stopbands. Figure 9 shows similar results. That is, both greater and smaller \(Z_e/Z_o\), even-mode impedance/odd-mode impedance, cause a higher attenuation level with the proposed filter in both the “on” and “off” states. Nevertheless, narrower bandwidths of dual stopbands result.

According to Figures 6 and 7, a higher attenuation within the stopband will be obtained with a smaller impedance \(Z_1\) or greater impedance \(Z_2\). Taking the limitation of PCB fabrication into consideration, impedances \(Z_1\) and \(Z_2\) are chosen as 16.5 and 120 Ω, respectively. Consequently, by setting seven
normalised transmission zeros as 0.5, 0.6, 0.8, 1, 1.2, 1.4, and 1.5, the remaining parameters can be calculated with the aid of transmission zeros (7)–(13) derived in the previous section. Table 1 presents exemplary parameters of the proposed bandstop filter in the “on” and “off” states. Moreover, Figure 10 shows the theoretically simulated results.

4 | FABRICATION OF THE PROPOSED BANDSTOP FILTER

With the central frequency at 2 GHz, a switchable bandstop filter in the “on” state is taken as a design example herein. This bandstop filter is fabricated on the Rogers RO4003C substrate, whose dielectric constant, loss tangent, and layer thickness are 3.55, 0.0027, and 0.813 mm, respectively. With the assistance of electromagnetic (EM) simulator IE3D, theoretical parameters shown in Table 1 can be transformed into a physical circuit size, as indicated in Table 2. In addition, its layout is provided in Figure 11. In order to miniaturise the circuit size, a wide width of a transmission line with impedance $Z_1 = 16.5 \Omega$ can be divided into two halves and meandered these transmission lines. Herein, the PIN diode, BAP70_03 made by NXP Semiconductors, is adopted for the switchable circuit shown in Figure 11(b). The equivalent circuits of the PIN diode operating at 5 V (“on” state) or at 0 V (“off” state) are shown in Figure 11(c). Because $I_{\text{on}}$ appears in the “on” state, required $\theta_2$ and $Z_4$ in Table 1 should be modified as 20° and 146 Ω, respectively.

Figure 12(a) indicates that with the proposed bandstop filter in the “on” state, measured insertion loss greater than 30 dB
results in an ultra-wide stopband bandwidth of 110%, from 0.93 to 3.2 GHz. On the other hand, Figure 12(b) shows that with the bandstop filter in the “off” state, dual stopbands will appear.

5 | CONCLUSION

A compact bandstop filter with switchable functions is developed for wireless communication systems. A switchable circuit with PIN diodes is utilised to make a single ultra-wide stopband and dual wide stopbands. An exemplary bandstop filter with central frequency operated at 2 GHz is fabricated on Rogers RO4003C substrate with a thickness of 0.813 mm, and occupying an area of 29.3 × 29.7 mm. The measured results show that for the proposed circuit in the “on” state, the bandwidth of an ultra-wide stopband is 110% with an insertion loss greater than 30 dB. Moreover, for the proposed circuit in the “off” state, measured insertion losses within dual stopbands are all greater than 30 dB. In addition, agreement between theoretical and measured results validates the proposed circuit.

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FIGURE 12 Measured results of the proposed bandstop filter: (a) “on” state; (b) “off” state

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