Abstract — In this paper, a novel dual-wideband bandpass filter (BPF) is presented by using quarter-wavelength open stub loaded half-wavelength coupled-line. Equivalent voltage-current analysis method is applied to analyze this structure, which shows it has two tunable transmission zeros and dual-wideband frequency response. As an example, a dual-wideband BPF covering 1.228/1.57/6.8 GHz for GPS (Link 1 and Link 2) and RFID applications is designed, fabricated and measured. The fabricated filter has a compact size of $0.043\lambda_g \times 0.213\lambda_g$. The measured results show that the fabricated filter has the merits of low insertion loss, good return loss and high band-to-band isolation. The proposed dual-band BPF also has a very simple physical topology and quick design procedure.

Index Terms — Bandpass filter (BPF), coupled-line, dual-wideband, stub-loaded resonator.

I. INTRODUCTION

Modern dual-mode communication system requires a dual-band bandpass filter (BPF) to enhance the electrical performance of the radio frequency end. In recent years, many structures have been proposed to meet the above requirement. In [1], two sets of uniform-impedance half-wavelength resonators are used to design a dual-narrowband BPF for 1.8 GHz DCS and 2.4 GHz WLAN applications. A dual-passband BPF with multi-spurious suppression is realized by using asymmetrical stepped-impedance resonators in [2]. In [3], compact dual-band BPFs with controllable bandpasses are proposed by using stub loaded multiple-mode resonator. In [4], the quad-mode resonator is applied to design a compact and high-selectivity dual-mode dual-band BPF. Modified coupled-line is another effective structure to design dual-band BPF. It is widely known that coupled-line is a classical structure used in single-band BPF design, mainly due to its compact 1-D planar physical configuration and high passband selectivity. In [5,6], S. Lee and Y. Lee firstly introduce capacitive or inductive stubs in traditional coupled-line structure to achieve dual-band frequency response, and the transverse dimension of coupled-line-type BPF is decreased simultaneously. However, these two dual-band BPFs suffer from relatively large circuit size, complicated physical topology and design procedure. In the author’s previous work [7,8], two stub loaded coupled-line dual-band BPFs have been proposed, and a good filter performance and compact circuit size has been achieved. Nevertheless, the insertion loss in [7] and out-of-band rejection in [8] need further improvements. In addition, the bandwidth in [7] cannot meet the requirement of modern dual high-data-rate communication system.

In this paper, a novel quarter-wavelength open stub loaded half-wavelength coupled-line is proposed, which has dual-band frequency performance. By using a half-wavelength transmission line to cascade the proposed two stub loaded coupled-line, a dual-wideband BPF with large dual-band central frequency ratio can be designed. As an example, a dual-wideband BPF for 1.228/1.57 GHz GPS and 6.8 GHz RFID applications is designed, fabricated and measured. Equivalent voltage-current analysis method is applied to analyze this dual-band BPF, and the corresponding design rules are given for the filter design.

II. THEORY ANALYSIS

A. ABCD parameters and S parameters

Figure 1 (a) gives the transmission line model of proposed dual-wideband BPF. It consists of two quarter-wavelength open stub loaded half-wavelength coupled-line and one half-wavelength transmission line. In order to analyze this structure, equivalent voltage and current analysis method is used, and the corresponding model is given in Fig. 1 (b). Thus, the ABCD parameters of proposed dual-wideband BPF can be given as follows:
where
\[
\begin{bmatrix}
    A_e & B_e \\
    C_e & D_e
\end{bmatrix} = \begin{bmatrix}
    A_{i,i} & B_{i,i} \\
    C_{i,i} & D_{i,i}
\end{bmatrix}\begin{bmatrix}
    A_o & B_o \\
    C_o & D_o
\end{bmatrix},
\]
(1)

If even-mode electrical length of coupled-line (\(\theta_e\)) equaling to odd-mode electrical length of coupled-line (\(\theta_o\)) are assumed, the following two equations can be obtained from the \([9]\) as follows:
\[
\begin{bmatrix}
    v_1 - v_2 \\
    i_1 - i_2
\end{bmatrix} = \begin{bmatrix}
    \cos(2\theta) & jZ \sin(2\theta) \\
    jY \sin(2\theta) & \cos(2\theta)
\end{bmatrix}\begin{bmatrix}
    v_4 - v_3 \\
    -i_4 + i_3
\end{bmatrix},
\]
(2a)

\[
\begin{bmatrix}
    v_1 + v_2 \\
    i_1 + i_2
\end{bmatrix} = \begin{bmatrix}
    \cos(2\theta) & jZ \sin(2\theta) \\
    jY \sin(2\theta) & \cos(2\theta)
\end{bmatrix}\begin{bmatrix}
    v_4 + v_3 \\
    -i_4 + i_3
\end{bmatrix},
\]
(2b)

where
\[
Z_{oo} = Z_c \sqrt{(1+k_c)/(1-k_c)} 
Y_{oo} = 1/Z_{oo},
\]
\[
Z_{eo} = Z_c \sqrt{(1-k_c)/(1+k_c)} 
Y_{eo} = 1/Z_{eo}.
\]

The coupled-line in Fig. 1 (b) has the boundary condition of \(v_i = -iZ_c' = jZ_c \cot \theta\) and \(v_i = 0\). After substituting these two conditions into the equations (2), the \(ABCD\) matrix of quarter-wavelength open stub loaded half-wavelength coupled-line can be derived as:
\[
\begin{bmatrix}
    A_{ii} & B_{ii} \\
    C_{ii} & D_{ii}
\end{bmatrix} = \begin{bmatrix}
    u_1 & -u_3 + u_6 \\
    u_4 - u_6 & u_5
\end{bmatrix},
\]
(3a)

\[
\begin{bmatrix}
    A_{oo} & B_{oo} \\
    C_{oo} & D_{oo}
\end{bmatrix} = \frac{1}{u_4 u_5 - u_6 u_6} \begin{bmatrix}
    u_1 u_5 - u_3 u_6 & -u_6 u_6 + u_5 u_6 \\
    -u_5 u_5 & -u_4 u_5
\end{bmatrix},
\]
(3b)

where
\[
u_1 = -j[(Z_{oo} + Z_{eo}) \sin(2\theta)]/2, 
\]
\[
u_2 = -\cos(2\theta),
\]
\[
u_3 = j[(Z_{eo} - Z_{oo}) \sin(2\theta)]/2, 
\]
\[
u_4 = [Y_{oo} - Y_{eo}] Z_c \cot \theta \sin(2\theta)]/2,
\]
\[
u_5 = -j[(Z_{eo} - Z_{oo}) \sin(2\theta)]/2,
\]
\[
u_6 = j[2Z_c \cot \theta \cos(2\theta) - (Z_{oo} + Z_{eo}) \sin(2\theta)]/2, 
\]
\[
u_7 = -\frac{2 \cos(2\theta) + (Y_{oo} + Y_{eo}) Z_c \cot \theta \sin(2\theta)}{2}.
\]

Since the proposed dual-wideband BPF is symmetrical, its \(S\)-parameters can be then given by:
\[
S_{11} = S_{22} = \frac{A_e + B_e / Z_o - C_e Z_o + D_e}{A_e + B_e / Z_o + C_e Z_o + D_e},
\]
(4a)

\[
S_{12} = S_{21} = \frac{2(A_e D_o - B_e C_o)}{A_e + B_e / Z_o + C_e Z_o + D_e},
\]
(4b)

\[
\begin{align*}
Z_{oo}, k_c, 2\theta & \\
Z_{eo}, k_c, 2\theta &
\end{align*}
\]

Fig. 1. (a) Transmission line model of proposed dual-wideband BPF, and (b) equivalent voltage and current analysis model.

B. Transmission zeros

The transmission zeros of proposed dual-wideband BPF is dependent on the quarter-wavelength open stub loaded half-wavelength coupled-line and independent on the half-wavelength transmission lines, so that the transmission zeros satisfy:
\[
A_{ii} D_{ii,0} B_{ii} C_{ii,0} = 0.
\]
(5)

After simplifying the equations (3), it can be derived that:
\[
u_4 u_5 = u_6 u_6.
\]
(6)

When \(\theta = 0, \pi/2\) and \(\pi\) at the designing frequency \(f_0\), respectively, it can be verified that the equation (6) is built. Thus, the proposed dual-wideband BPF has fixed transmission zeros at 0, \(f_0\) and 2\(f_0\), respectively, within the frequency range \([0, 2f_0]\). Substituting \(u_6 u_5\) into the equation (6), it can be gotten that:
\[
\tan^2 \theta = \left( \frac{Z_c \sqrt{1 - k_c^2} + 4Z_c}{Z_c \sqrt{1 - k_c^2}} \right) \left( \frac{Z_c \sqrt{1 - k_c^2}}{} \right).
\]
(7)

The proposed dual-wideband BPF has a pair of tunable transmission zeros which are symmetrical along \(f_0\). Its frequency locations are given as follows:
\[
f_{i1} = \frac{2 f_0}{\pi} \arctan \left( \frac{Z_c \sqrt{1 - k_c^2} + 4Z_c}{Z_c \sqrt{1 - k_c^2}} \right),
\]
(8a)

\[
f_{i2} = \frac{2 f_0}{\pi} \left( \pi - \arctan \left( \frac{Z_c \sqrt{1 - k_c^2} + 4Z_c}{Z_c \sqrt{1 - k_c^2}} \right) \right).
\]
(8b)
These two transmission zeros have the relationship of \(0 < f_{z1} < f_0 < f_{z2} < 2f_0\), and repeat at every frequency range \([2nf_0, (n+1)f_0]\), where \(n\) is an integer.

C. Design rules

It can be verified that the proposed dual-wideband BPF has a symmetrical frequency response along the design frequency \(f_0\). That is, two passbands of the proposed dual-wideband BPF has an equal value of absolute bandwidth \(BW\). Under the initial designing parameters of \(Z = 140\, \Omega\) and \(k_c = 0.4\), Fig. 2 plots the variation of \(f_{z2}/f_{z1}\) and \(BW/f_0\) versus different values of \(r_c = Z_c/Z\) and \(r_s = Z_s/Z\), where \(f_{z1}\) and \(f_{z2}\) represents the central frequency of the first and second passband, respectively. It can be seen in Fig. 2 that \(f_{z2}/f_{z1}\) increases as \(r_c\) increases, but it decreases as \(r_s\) increases. It can be also seen in Fig. 2 that \(BW\) increases as \(r_c\) increases, and as \(r_s\) increases, \(BW\) increases firstly but then decreases. Figure 3 gives the variation of \(|S_{21}|\) and \(|S_{11}|\) versus different values of \(Z\) and \(k_c\) under fixed \(r_c = r_s = 1.0\). It can be seen in Fig. 3 (a) that \(Z\) has minor effect on \(|S_{21}|\) but it can be used to tune the \(|S_{11}|\) slightly. It can be seen in Fig. 3 (b) that the BW of two passbands becomes wide as \(k_c\) increases.

In summary, in the dual-wideband design process, the designing parameters \(r_s\) and \(r_c\) can be tuned to achieve the desired frequency position of two passbands. The designing parameter \(k_c\) can be used to control the \(BW\) of two passbands and the designing parameter \(Z\) can be then tuned to acquire a good return loss. In addition, it should be noted that the BW of two passbands cannot be controlled individually due to its symmetrical frequency response.

Fig. 2. Variation of \(f_{z2}/f_{z1}\) and \(BW/f_0\) versus different values of \(r_c\) and \(r_s\).

Fig. 3. Variation of \(|S_{21}|\) and \(|S_{11}|\) versus different values of: (a) \(Z\) (\(k_c = 0.4\) fixed), and (b) \(k_c\) (\(Z = 140\, \Omega\) fixed).

III. SIMULATION AND MEASUREMENT

According to the above discussion, the initial designing parameters of dual-wideband BPF are pre-selected as \(Z_c = 147\, \Omega, k_c = 0.42, Z = 140\, \Omega\) and \(Z_s = 150\, \Omega\), under which the first passband covers 1.228/1.575 GHz and the second passband covers 6.8 GHz. The dual-wideband BPF is designed on the substrate ARlon DiClad 880 (\(\varepsilon_r = 2.2, h = 0.508\, \text{mm}, \tan\delta = 0.0009\)).

Figure 4 (a) gives the layout of fabricated dual-wideband BPF. In Fig. 4 (a), the half-wavelength microstrip line and the loaded quarter-wavelength stubs are folded, so as to achieve size reduction. The whole structure is optimized by using the full wave EM simulator HFSS to consider the impact of bends, the grounded vias, the impedance discontinuities and the unequal even-/odd-mode phase velocities. The optimized physical dimensions are also labeled in Fig. 4 (a). Figure 4 (b) shows the photograph of fabricated dual-wideband BPF with the circuit size of \(0.043\lambda_g \times 0.213\lambda_g\), where \(\lambda_g\) represents the guided wave-length of 50 \(\Omega\) microstrip line at the central frequency of the first passband.
The simulated and measured results of fabricated dual-band BPF are plotted in Fig. 5. Good agreement can be observed between the simulation and measurement. There are some discrepancies which are attributed to the fabrication error as well as SMA connectors. The measured central frequencies (CFs) and 3 dB FBW of two passbands are 1.54 GHz / 6.88 GHz and 60%/11.5%, respectively. The measured insertion losses (ILs) at 1.228 GHz, 1.575 GHz and 6.8 GHz are 0.4 dB, 0.4 dB and 0.9 dB, respectively. The return losses of two passbands are better than 26 dB and 15 dB, respectively. The band-to-band isolation is better than 20 dB from 2.5 GHz to 6.1 GHz.

Table 1 gives a performance comparison with some reported coupled-line-type dual-band BPF. In Table 1, CF, FBW and IL represents the central frequency, fractional bandwidth and insertion loss, respectively. After comparison, it obviously shows that the proposed dual-wideband BPF has the merits of low insertion loss, compact circuit size, wide passband, large dual-band central frequency ratio, simple physical topology and quick design procedure.

### Table 1: Performance comparison with some reported coupled-line-type dual-band BPFs

<table>
<thead>
<tr>
<th></th>
<th>CF (GHz)</th>
<th>3 dB FBW</th>
<th>IL at CF (dB)</th>
<th>Circuit Size ($\lambda_0^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref. [5]</td>
<td>2.4, 5.2</td>
<td>8%, 3.69%</td>
<td>1.6, 2.5</td>
<td>0.189×0.733</td>
</tr>
<tr>
<td>Ref. [6] (Filter B)</td>
<td>2.0, 5.0</td>
<td>12%, 3%</td>
<td>1.0, 3.0</td>
<td>-</td>
</tr>
<tr>
<td>Ref. [7] (Filter A)</td>
<td>2.4, 5.8</td>
<td>5.8%, 2.1%</td>
<td>1.59, 2.59</td>
<td>0.312×0.304</td>
</tr>
<tr>
<td>Ref. [8] (Filter B)</td>
<td>2.48, 6.63</td>
<td>43.2%, 16.5%</td>
<td>0.33, 0.74</td>
<td>0.12×0.17</td>
</tr>
<tr>
<td>This Work</td>
<td>1.54, 6.88</td>
<td>60%, 11.5%</td>
<td>0.4, 0.9</td>
<td>0.043×0.213</td>
</tr>
</tbody>
</table>

### IV. CONCLUSION

A dual-wideband BPF covering 1.228/1.57/6.8 GHz for GPS (Link 1 and Link 2) and RFID applications is presented by using proposed quarter-wavelength open stub loaded half-wavelength coupled-line. The fabricated dual-wideband BPF has a compact circuit area of 0.043$\lambda_0$ × 0.213$\lambda_0$. Measured results also show its merits of low insertion loss, good return loss, sharp passband selectivity and good band-to-band isolation. The proposed filter has simple topology and design procedure. All these merits make it attractive in modern dual-wideband communication system.

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