A novel ultra-wideband bandpass filter using defected microstrip structures

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\textbf{Abstract:} A novel ultra-wideband (UWB) bandpass filter with compact size, improved stopband performance and wider bandwidth is presented in this paper. A new defected microstrip structures resonator (DMSR) is proposed and analyzed theoretically. In order to improve the stopband characteristics, three interdigitated parallel coupled-lines (IPCL) and two complementary split ring resonators (CSRR) are adopted. Finally, a filter prototype is fabricated and measured. The measured results show that the proposed filter achieves a bandwidth of 129\% from 2.35 to 10.8 GHz. And the insertion loss is less than 0.5 dB with good return loss.

\textbf{Keywords:} bandpass filter (BPF), ultra-wideband (UWB), defected microstrip structures (DMS), complementary split ring resonator (CSRR)

\textbf{Classification:} Microwave and millimeter wave devices, circuits, and systems

\textbf{References}

1 Introduction

Ultra-Wideband (UWB) technology has great potential in the development of various modern wireless systems, such as, through-wall imaging, medical imaging, vehicular radar, indoor, and hand-held UWB systems [1]. Since the use of the ultra-wideband (UWB) frequency spectrum (3.1–10.6 GHz) is unlicensed by the Federal Communications Committee (FCC), it has attracted countless attention in both academic and industrial domains to study various UWB devices (antennas, UWB BPF, power divider, etc.) [2]. As a key passive component in the UWB systems, UWB bandpass filter has received great development in recent years. At the same time, different methods and structures have been proposed to develop new UWB filters with good performances [3, 4, 5, 6, 7, 8, 9, 10, 11]. For example, some ultra-wideband bandpass filters have been introduced via the hybrid microstrip and coplanar waveguide (CPW) [3, 4, 5]. However, the selectivity of this type of filters is not satisfactory because of no transmission zero at lower stopband. Various multi-mode resonators (MMR) have often been used to design UWB BPF, including the stub-loaded MMR with four modes in UWB band [6, 7, 8]. The stub-loaded MMR could improve the upper stop-band. In [9], a novel MMR was presented. Compared with the conventional MMR, the hairpin resonators used to construct the MMRs are located at the upper band-edge frequency. As a result, the proposed quadruple-mode UWB filter based on the connected hairpin MMRs had both good performances in-band and out-of-band. But this kind of UWB BPF inevitably suffered from relatively large size. In [10], the quarter-wavelength inverters-lines have been used to expand the bandwidth. However, this structure is not compact either. In [11], a new cascade connection of bandpass defected microstrip structures resonator (DMSR) has been used to implement a UWB bandpass filter. While its size and stopband characteristics are dissatisfactory. For instance, its upper stop-band frequency with 20 dB attenuation is lower than 14 GHz.

In this paper, a novel defected microstrip structures resonator (DMSR) is proposed to design an UWB bandpass filter (BPF). The resonant characteristics
of this DMSR are analyzed theoretically. Moreover, in order to better the lower stopband characteristics of the UWB filter (Fig. 2(b)), three interdigitated parallel coupled-lines (IPCL) are used at the middle of the defected microstrip structures (DMS). Meanwhile, two complementary split ring resonators (CSRR) are added at the input and output ports of DMS to expand the upper stopband. Therefore, two transmission zeros are generated at the lower and upper stopbands separately. And the mechanism of the two zeros is also explained. A prototype of the proposed filter has been fabricated and measured for verification. The measured results of the ultra-wideband (UWB) bandpass filter are in good agreement with the simulated ones.

2 The design and analysis of this UWB BPF

As shown in Fig. 1(a), the basic structure of the proposed DMSR is different from the general configuration of Complementary Open Ring-DMS (COR-DMS) in the microstrip, which has recently been presented by author in [12]. In this paper, a new compact wideband bandpass resonator is proposed. At first, the two open-end stubs are replaced by short-end stubs. Besides, two parallel defected microstrip structures are used, then the stopband performances can be improved. In addition, the transmission line model of the proposed DMSR is used to analyze this DMSR (Fig. 1(b)). And the odd-mode and even-mode methods can be used to study the presented DMSR for it is symmetrical with respect to the line T-T'.

For the even-mode excitation, the equivalent circuit could be obtained as shown in Fig. 1(c).

\[ Y_{in,even} = 2Y_1 - jY_3 \cot \theta_3 + jY_1 \tan \theta_1 + jY_2 \tan \theta_2. \]  \hspace{1cm} (1)

For the odd-mode excitation, the equivalent circuit is shown in Fig. 1(d).

\[ Y_{in,odd} = -j(2Y_1 \cot \theta_1 + Y_2 \cot \theta_2). \]  \hspace{1cm} (2)

With the hypothesis of \( \Theta_1 = \Theta_2 = \Theta_3 \), the resonance condition of \( Y_{in,even} = 0 \) and \( Y_{in,odd} = 0 \) could be solved as

\[ \theta_{even} = \arctan \sqrt{2Y_1 Y_2/(Y_1 Y_2 + Y_2 Y_3 + 2Y_1^2)}. \]  \hspace{1cm} (3)
\[ \theta_{\text{even}2} = \pi - \theta_{\text{even}1}; \quad \theta_{\text{odd}} = \pi / 2. \] (4)

Besides, with the condition of \( Y_{\text{in,even}} * Y_{\text{in,odd}} = Y_0^2 \), the transmission poles can be summarized by Eq. (5):

\[ \cot^2 \theta_p = \frac{(2Y_1^2 + Y_2(Y_1 + Y_3))(2Y_1 + Y_2) - Y_0^2(Y_1 + Y_3)/(2Y_1 Y_3(2Y_1 + Y_2))}{2Y_1 Y_3(2Y_1 + Y_2)}; \quad \theta_{\text{p1}} = \pi - \theta_{\text{p2}}. \] (5)

The solutions of Eq. (5) (\( \Theta_{\text{p1}} \) and \( \Theta_{\text{p2}} \)) are shown as follows:

\[ \theta_{\text{p1}} = \text{arc} \cot \sqrt{\frac{(2Y_1^2 + Y_2(Y_1 + Y_3))(2Y_1 + Y_2) - Y_0^2(Y_1 + Y_3)}{2Y_1 Y_3(2Y_1 + Y_2)}}; \quad \theta_{\text{p2}} = \pi - \theta_{\text{p1}}. \] (6)

With the admittance condition of \( Y_0 = 2Y_1 + Y_2 \), \( \Theta_{\text{p3}} = \pi / 2 \) is the third pole (Ignoring the \( \lambda / 4 \) short-end stubs, three microstrip lines are equivalent to one line, due to the same electrical length \( \Theta_1 = \Theta_2 \)).

The simulated results of the DMSR are shown in Fig. 2(a). It is clearly observed that the DMSR has a bandpass characteristic with three poles (calculated by \( \Theta_{\text{p1}}, \Theta_{\text{p2}} \) and \( \Theta_{\text{p3}} \)) in the UWB band.

Even though the DMSR has bandpass characteristic, it cannot be applied directly in UWB systems due to its bad selectivity. In this work, to obtain a UWB BPF with good out-of-band performances, the central microstrip of DMSR is replaced by the IPCL. Besides, two complementary split ring resonators (CSRR) are adopted to expand the upper stopband frequency. The layout of the whole filter is shown in Fig. 2(b), and the \( S_{21} \) of different structures are plotted in Fig. 2(c).

The IPCL is a traditional bandpass structure, which has two zeros at the electrical length of 0 and \( \pi \) [13] (the phase velocities of even- and odd-modes are thought as approximately equal). The transmission zero \( f_{\text{uz1}} \) (Fig. 2(c)) located at the upper stopband is caused by the IPCL at \( \pi \) electrical length, but the upper stopband rejection of DMSR+IPCL is still not satisfactory. To solve this problem, the zero \( f_{\text{uz2}} \) is added by the cascading CSRRs. The equivalent circuit of CSRR is a parallel LC resonator [14], which is a single zero (\( f_{\text{uz2}} \)) structure (Fig. 2(c)).
Besides, the lower stopband transmission zero $f_{lz}$ is introduced by the combining structure of DMSR+IPCL. In low frequency, this combining structure is equivalent to lumped model of Fig. 3(a). When the electrical length of IPCL is much less than $\pi/2$, the IPCL degenerates into an interdigitated capacitor $C_I$ [13]. Meanwhile, the short-length microstrip lines and the short-end stubs are approximated as inductor $L_1$ and $L_2$ separately in low frequency. Because the equivalent model of Fig. 3(a) is symmetrical with respect to the line $F-F'$, it can be analyzed by the odd-mode and even-mode methods. The odd mode (Fig. 3(b)) and even mode (Fig. 3(c)) impedances can be written as Eq. (7). Then the transmission zero condition of $Z_{in,odd} = Z_{in,even}$ can be solved as Eq. (8), which is the lower stopband transmission zero $f_{lz}$.

$$Z_{in,odd} = 0.5 j\omega L_1/(1 - \omega^2 L_1 C_I); \quad Z_{in,even} = 0.5 j\omega (L_1 + L_2).$$

$$2\pi f_{lz} = \omega_{lz} = \sqrt{(1 - L_1/(L_1 + L_2))/L_1 C_I).$$

3 Experimental results and discussion

![Fig. 4. Pictures of the fabricated UWB BPF (a) top view, (b) bottom view.](image)

![Fig. 5. Dimensions of this UWB BPF](image)

Table 1. Comparison between the proposed UWB BPF and others

| Ref. | S.F. | $\Delta f_{3dB}$ | $\Delta f_{30dB}$ | $|S11|$ | $|S21|$ | $F_c$ (GHz) | Size ($\lambda_g \times \lambda_g$) |
|------|------|-----------------|-----------------|--------|--------|-------------|-------------------|
| [3]  | 0.7  | 109%            | >10             | <1.8   | 15     | 0.90 x 0.29 |                   |
| [4]  | 0.5  | 95%             | >11             | <1.83  | 16     | 3.38 x 1.11 |                   |
| [6]  | 0.92 | 110%            | >10.5           | NG     | 17.1   | 0.82 x 0.50 |                   |
| [7]  | 0.86 | 115%            | >9.5            | NG     | 17.6   | 0.58 x 0.47 |                   |
| [8]  | 0.90 | 117%            | >11.1           | <1.4   | 29.7   | 0.74 x 0.54 |                   |
| [9]  | 0.82 | 103%            | >14             | <0.6   | 15.1   | 0.94 x 0.63 |                   |
| [11] | 0.65 | 110%            | >10             | <1     | 13.5   | 1.67 x 0.08 |                   |
| This Work | 0.7  | 129%            | >13.5           | <0.5   | 18     | 0.51 x 0.12 |                   |

S.F.: selectivity factor of the passband; $\Delta f_{3dB}$, $\Delta f_{30dB}$: 3 dB bandwidth and 30 dB bandwidth of the passband; $F_c$: the upper stopband frequency with 20-dB attenuation; $\lambda_g$: the guided wavelength at 6.85 GHz; NG: Not given.
According to the above analysis, an UWB bandpass filter has been designed. As shown in Fig. 4, a prototype of the proposed BPF has been fabricated on Rogers RT5880. The substrate has a relative permittivity 2.2 and its thickness is 0.787 mm. The filter is simulated and optimized using commercial software HFSS. The final dimensions of the fabricated UWB BPF are (see Fig. 5): \( w_0 = 2.4 \text{ mm}, l_0 = 6 \text{ mm}, w_{s1} = 0.8 \text{ mm}, w_3 = 0.12 \text{ mm}, l_{s2} = 7.19 \text{ mm}, d_{s1} = 0.8 \text{ mm}, l_{c1} = 7.2 \text{ mm}, l_{s1} = 0.21 \text{ mm}, w_{s2} = 0.33 \text{ mm}, w_{s3} = 1.04 \text{ mm}, w_{s4} = 0.11 \text{ mm}, w_{c1} = 0.21 \text{ mm}, s_0 = 0.11 \text{ mm}, g_0 = 0.11 \text{ mm}, g_1 = 0.14 \text{ mm}, w_{c2} = 0.16 \text{ mm}, a = 0.99 \text{ mm}, b = 0.18 \text{ mm}, c = 0.21 \text{ mm}, d_0 = 0.26 \text{ mm}, w_{dgs} = 0.7 \text{ mm}, l_{dgs} = 6.48 \text{ mm}.

Table I is the comparison of the proposed UWB BPF and previously published works. The proposed UWB BPF presents good in-band filtering performance (insertion loss less than 0.5 dB), compact size of \( 0.51\lambda_g \times 0.12\lambda_g \), and wider bandwidth (the 3 dB passband covers the range of 2.35–10.8 GHz). From the simulated and measured results of the proposed UWB BPF (Fig. 6), it could be obviously observed that the simulated and measured results are matched well.

![Simulated and measured results of the fabricated UWB BPF.](image)

**Fig. 6.** Simulated and measured results of the fabricated UWB BPF.

### 4 Conclusion

In this paper, a novel compact bandpass defected microstrip structures resonator (DMSR) is presented and analyzed. It has bandpass characteristic with three transmission poles. To achieve a DMSR-based UWB bandpass filter, three interdigitated parallel coupled-lines (IPCL) are introduced to improve the lower frequency selectivity, and two cascading complementary split ring resonators (CSRR) are added to expand the upper stopband to 18 GHz. A prototype of this filter has been fabricated and measured for verification. The measured results represent low passband insertion loss (0.5 dB), good return loss and wider bandwidth (129%). This filter is compact \( 0.51\lambda_g \times 0.12\lambda_g \), simple, and attractive for UWB application.

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