A compact filtering UWB antenna with band-notched function

Hailong Yang¹, Xiaoli Xi¹,²a), Yuchen Zhao¹, Lili Wang¹, and Xiaomin Shi³
¹ Electronic Engineering Department, Xi’an University of Technology, Xi’an 710048, People’s Republic of China
² Science and Technology on High Power Microwave Laboratory, Northwest Institute of Nuclear Technology, Xi’an 710024, China
³ Communication Engineering Department, Xi’an Shiyou University, Xi’an, People’s Republic of China
a) xixiaoli@xaut.edu.cn

Abstract: A compact filtering UWB antenna with band-notched function is proposed. The proposed antenna mainly consists of a stepped impedance resonator feeding line with low-pass characteristic at the top of the dielectric substrate and two slots at the bottom. The stepped impedance resonator is used to enhance the upper band-edge selectivity, and the narrow slot near the stepped slot is employed to improve the lower band-edge selectivity. What’s more, two microstrip lines paralleling to the feeding line are located at the end of the slot, which can generate the notch band by controlling the length of the current path in two microstrip lines. Compared with the traditional antennas, the proposed antenna is not only smaller in size, but also has better suppression of the in-band and out-of-band interference signals in function.

Keywords: ultra-wideband (UWB) slot antenna, band-edge selectivity, low-pass filter

Classification: Microwave and millimeter-wave devices, circuits, and modules

References

1 Introduction

Ultra-wideband (UWB) technology has obtained great development since the U.S. Federal Communications Commission allocated the 3.1–10.6 GHz frequency band for commercial UWB systems [1]. It has been applied in different areas, such as short-range technology for wireless communication, Wireless body area net work (WBAN), UWB radar and imaging systems with superior penetration and high resolution [2]. As a critical part of the UWB system, the UWB antenna attracts more attention owing to its advanced characteristics, such as lightweight, easy integration, and low cost.

In practical applications, the flat bandwidth of the UWB antenna may lead to other unwanted signals out-of-band or in-band, which will affect the performance of the receiver. For unwanted out-of-band signals, traditionally, the antenna will
always be followed by a band-pass filter to suppress unwanted frequencies and to improve the band-edge frequency selectivity of the whole system [3]. However, in this kind of design philosophy, in which the antennas and the filters will increase the size and cost of the RF front-end, which are independent of each other respectively [4]. Hence, a UWB antenna with filter function is of great importance in reducing both the size and cost of the UWB system. To the best of our knowledge, most of the UWB antenna designs focus on the minimization technology [5], band-notched characteristics [6, 7, 8] and other antenna performances, such as high gain and wide bandwidth [9, 10, 11]. However, the band-edge selectivity and the size of these antennas are not satisfactory. In [12, 13], the radiating patch is electromagnetically coupled to a UWB filter to achieve frequency selectivity. For these antennas, the feeding lines are designed with filtering characteristics, which will increase the length of the feeding lines. Although the shape factor is reduced to 1.078 [12] and 1.08 [13], the size of the antenna is 53 mm × 22 [12] and 53 mm × 42 mm [13], which are still relatively large. For in-band interference, the antenna usually uses slot [7, 8, 14] or parasitic structure [15]. In [16], Wong et al. proposed a planar filtering UWB antenna with four shorting pins to achieve desired selectivity properties, and the size is compact with an overall dimension of 28.5 mm × 28 mm. Unfortunately, the selectivity of this filtering antenna and the notched band are not controlled and changed easily.

In this work, a novel compact filtering UWB antenna with improved band-edge selectivity and the notched band is proposed. First, a stepped impedance resonator with low pass filtering characteristics is applied to replace the 50Ω microstrip feeding line. The band-edge selectivity at high frequencies and the size of the antenna are improved significantly. Then, an additional narrow slot, which is located near the stepped slot, not only improves the frequency selection characteristics but also enhances the bandwidth at low operation frequency. Furthermore, to reject some narrow interference signals in-band, such as the wireless local area networks (WLAN) for operating frequency in the 5.15–5.35 GHz and 5.725–5.825 GHz and the worldwide interoperability for microwave access (WiMAX) with the frequency of 3.3–3.7 GHz, two microstrip lines parallelling to the feeding line are added. The design of notch frequency can be adjusted by controlling the current patch on the microstrip line, which is more simple and convenient. The size of the proposed antenna is 24 mm × 12 mm, which is smaller than that of the relevant works in [2, 4, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16]. The ratio of the −3 dB bandwidth to the −10 dB bandwidth is 1.038, which is very close to 1. Additionally, the reflection coefficient of the proposed antenna is steeper and has a better shape factor as compared to the antenna in [13], and [16], which has improved about 4%, and 7.8%, respectively. The measured results of the time domain and frequency domain meet the designed requirements, which verify the model as a good candidate for UWB applications.

2 Antenna design

The proposed slot antenna with improved band-edge selectivity is shown in Fig. 1(a). The size of the proposed antenna is 24 mm × 12 mm, which is printed
on a 0.787 mm thick RT/Duroid 5880 substrate. The relative permittivity of the substrate is 2.2, and the loss tangent is 0.018. The proposed antenna mainly consists of a low pass stepped microstrip filter (Fig. 1(b)) at the top of the dielectric substrate, and two slots at the bottom. The low-pass filter decides the location of upper band-edge selectivity and the narrow slot near the stepped slot improves the lower band-edge selectivity. At the end of the slot, there are two microstrip line parallel to the feeding microstrip line, which can generate the notch band by controlling the length of the current path in the microstrip line.

The evolution of the proposed slot antenna is shown in Fig. 2, and the corresponding reflection coefficients are compared in Fig. 3. Fig. 2(a) illustrates the basic model (Type-A) of the antenna. As shown in Fig. 3, the frequency selectivity of the Type-A antenna is inferior, and the starting frequency at low-frequency is 3.75 GHz, which does not meet the 3.1 GHz ultra-wideband require-

![Image](image1.png)

**Fig. 1.** Geometry of the proposed antenna and S-parameters curve of the low pass stepped microwave filter feeding line.  
(a) Geometry of the proposed antenna,  
(b) Simulated S-parameters of the stepped microstrip filter.

![Image](image2.png)

**Fig. 2.** The evolution of the proposed slot antenna, (a) Type-A, (b) Type-B, (c) Type-C, (d) Type-D.

![Image](image3.png)

**Fig. 3.** Comparison of simulated reflection coefficients of the antennas proposed in Fig. 2.
ment. The size of Type-A antenna is 24 mm × 16 mm. Fig. 2(b) shows an improved design, where the microstrip feeding line is replaced by a stepped-impedance microstrip line with low pass characteristics. As can be seen in Fig. 3, one reflection zero \( f_2 \) is created at the upper stopband. In this way, the reflection coefficient of the upper band becomes steeper. Compared with the Type-A curve, the upper band-edge selectivity of the Type-B antenna is improved significantly, the starting frequency at low-frequency band is also reduced from 3.75 GHz to 3.5 GHz. Both the slot length and the antenna size are reduced. The length of the stepped slot decreased from 13 mm to 11 mm. The size of the Type-B antenna is reduced to 24 mm × 12 mm, which is much smaller than Type-A antenna.

To further increase the bandwidth of the antenna, specifically at low-frequency end, a narrow slot near the stepped slot is added, shown as Type-C in Fig. 2(c). As we all know, the first resonant frequency of slot antenna mainly depends on the size of the antenna and the total length of the slot. However, the controllable range is limited because of the small size of the antenna. To improve this, as seen in Fig. 4(a), by adding a narrow slot near the stepped slot, the first resonance frequency is further reduced by prolonging the current path. As seen in Fig. 4(b), the first resonance frequency is further reduced by prolonging the current path, and the lower band-edge selectivity is improved with an additional reflection zero \( f_1 \). The bandwidth at a lower frequency is also improved from 3.5 GHz–11 GHz (103%) to 3.1 GHz–11 GHz (112%).

![Fig. 4. (a) Reflection coefficient curves of Type-B antenna with different slot lengths. (b) The current distribution of the Antenna with and without narrow slot at 3.2 GHz.](image)

The Type-C antenna can be further improved in terms of better in-band interference suppression, such as 3.3–3.7 GHz WiMAX band and the 5.15–5.825 GHz WLAN band. For this purpose, two microstrip lines with connecting hole are added, leading to the Type-D design as shown in Fig. 2(d). The current flows from the microstrip line through connecting hole to the ground. The notch frequency is related to the length of the current path, as shown in Fig. 5. The range of regulation is 3.3–5.5 GHz. The longer the current path, the lower the notch frequency. Therefore, the notch frequency band can be adjusted easily by controlling the current path.
Table I shows the comparison of the antenna characteristics of the four designs. Lstep is the length of the stepped slot. To evaluate the band-edge selectivity of the UWB antenna effectively, a shape factor $K$ is defined as $K = \frac{BW_{-3dB}}{BW_{-10dB}}$, where $BW_{-3dB}$ and $BW_{-10dB}$ are $-3$ dB and $-10$ dB bandwidth of the antenna. The band-edge selectivity of a UWB antenna is considered good when $K$ is close to 1.

As can be seen from the Table I, the bandwidth, size and frequency selection characteristics out-of-band and in-band of Type-D antenna have been significantly improved.

![Reflection coefficients of the antenna with different current path length of Ls.](image)

**Fig. 5.** Reflection coefficients of the antenna with different current path length of Ls.

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Size (mm$^2$)</th>
<th>LStep (mm)</th>
<th>$BW_{-10dB}$ (GHz)</th>
<th>Shape Factor $K$</th>
<th>Notch Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type-A</td>
<td>24 x 16 = 384</td>
<td>13</td>
<td>3.75–15</td>
<td>&gt;1.64</td>
<td>Without</td>
</tr>
<tr>
<td>Type-B</td>
<td>24 x 12 = 288</td>
<td>11</td>
<td>3.5–11</td>
<td>1.1</td>
<td>Without</td>
</tr>
<tr>
<td>Type-C</td>
<td>24 x 12 = 288</td>
<td>11</td>
<td>3.1–11</td>
<td>1.038</td>
<td>Without</td>
</tr>
<tr>
<td>Type-D</td>
<td>24 x 12 = 288</td>
<td>11</td>
<td>3.1–11</td>
<td>1.038</td>
<td>3.3 and 5.5 GHz</td>
</tr>
</tbody>
</table>

Table I shows the comparison of the antenna characteristics of the four designs. Lstep is the length of the stepped slot. To evaluate the band-edge selectivity of the UWB antenna effectively, a shape factor $K$ is defined as $K = \frac{BW_{-3dB}}{BW_{-10dB}}$, where $BW_{-3dB}$ and $BW_{-10dB}$ are $-3$ dB and $-10$ dB bandwidth of the antenna. The band-edge selectivity of a UWB antenna is considered good when $K$ is close to 1. As can be seen from the Table I, the bandwidth, size and frequency selection characteristics out-of-band and in-band of Type-D antenna have been significantly improved.

![L-C ladder equivalent model of the step microstrip line.](image)

**Fig. 6.** L-C ladder equivalent model of the step microstrip line. (a) Microstrip layout of final filter. (b) Low-pass filter prototype circuit.

The length of the slot is 13 mm which is about $1/4\lambda$ of the first resonance frequency. The Slot antenna structure is relatively simple, and it is easy to realize miniaturization by changing the slots or feeding line [5, 6, 7].

In [5], a novel miniaturized slot antenna has been designed by using the multi-section slot and multi-section load of the feed line. Inspired by the document [5], a stepped impedance feed line with low pass filtering effect is designed, which not only reduces the size of the antenna but also improves the frequency selective characteristics at high frequency. In this way, RF front-end does not need filters, and the size and cost of RF front-end will be greatly reduced.
As shown in Fig. 1(b), the feed line is a stepped impedance filter in which the high impedance and low impedance microstrip lines are alternately arranged. Its equivalent circuit model is shown in the Fig. 6. Designing of a Chebyshev lowpass filter with the following parameters: 1) passband: 0–10.6 GHz; 2) the stop frequency: \( f_s = 13.5 \, \text{GHz} \); 3) Max attenuation in the passband: \( a_p = 0.1 \, \text{dB} \); 4) Min attenuation in the stop band: \( a_s = 30 \, \text{dB} \).

The mathematical modeling of the lowpass filter is done using equal-ripple low pass filter design approach [17]

\[
H(\omega) = \left( 1 + \varepsilon^2 T_n \left( \frac{\omega}{\omega_c} \right) \right)^{-1}
\]

Where \( \varepsilon \) is the coefficient of fluctuation which is a positive number less than 1, \( \omega_c \) is the cut-off frequency, \( T_n \) is Chebyshev polynomial of n order, which can be expressed as:

\[
T_n(\omega) = \begin{cases} 
\cos(n \cdot \cos^{-1}(\omega)) & |\omega| \leq 1 \\
\cosh(n \cdot \cosh^{-1}(\omega)) & |\omega| > 1 
\end{cases}
\]

For practical implementations, the highest characteristic impedance is elected as 110 \( \Omega \) (ZOH) and lowest characteristic impedance is chosen as 22 \( \Omega \) (ZOL). First find the required order of the maximally flat filter to satisfy the design requirements. The order \( n \) of the filter can be calculated from (3) [17], \( n = 9 \)

\[
n \geq \left[ \frac{\cosh(10\alpha_p/10 - 1)/(10\alpha_p/10 - 1)}{\cosh(\alpha_s/\alpha_p)} \right]
\]

Then the transmission line equivalent LC–ladder model for stepped impedance microstrip line is realized with component values obtained from equations (4) and (5) [17]. The normalized prototype value \( g_k \) can be obtained by looking up the table or calculated by equation (6) [17],

\[
C_k = \frac{g_k}{Z_0\omega_C}
\]

\[
L_k = \frac{Z_0g_k}{\omega_C}
\]

Where

\[
\begin{align*}
g_1 &= 2\alpha_1/\gamma \\
g_k &= 4\alpha_{k-1}\alpha_k/b_{k-1}g_k & k = 2, 3, \ldots, n \\
\alpha_k &= \sin\left(\frac{2k - 1}{2n}\pi\right) \\
b_k &= \beta^2 + \sin^2\left(\frac{k\pi}{n}\right)
\end{align*}
\]

The prototype element values as

\[
\begin{align*}
g_1 &= g_9 = 1.1956, & g_2 &= g_8 = 1.4425, \\
g_3 &= g_7 = 2.1345, & g_4 &= g_6 = 1.6167, \\
g_5 &= 2.2053.
\end{align*}
\]
Then (4) (5) can be used to obtain the LC–ladder model element values:

\[ L_1 = 0.54 \text{ nH} \]
\[ C_1 = 0.62 \text{ pF} \]
\[ L_2 = 1.17 \text{ nH} \]
\[ C_2 = 0.83 \text{ nH} \]
\[ L_3 = 0.563 \text{ nH} \]

Finally, the size of the low-impedance and high-impedance lines corresponding to the inductance and capacitance are obtained by further calculation. So, when the value of \( W_3 \), \( W_4 \) \( W_5 \) changes, the characteristics impedance and the corresponding capacitance and resonant frequency also change. As seen in Fig. 7, when the width of \( W_3 \) changes, the corresponding high impedance changes, which affects the choice of cut-off frequency. The width \( W_4 \) and \( W_3 \) are the low-impedance microstrip lines of step microstrip line, which corresponds to the capacitance in the equivalent circuit, and has a significant impact on the out-of-band suppression, sideband frequency selection and the highest reflection zero. The influence of the width \( W_3 \), \( W_4 \) and \( W_5 \) of the microstrip line on the performance of the antenna is also investigated. To obtain better selective characteristics at high frequency, both the width \( W_3 \), \( W_4 \) and \( W_5 \) effect on the reflection coefficient curve are shown in Fig. 8.

![Fig. 7](image)

Fig. 7. The reflection coefficient of the step microstrip line with the different width of \( W_3 \), \( W_4 \), and \( W_5 \).

It is clearly seen in Fig. 8(a) that when the other parameters fixed, with an increase in the width of \( W_3 \) from 0.3 mm to 0.5 mm, the center of the reflection zero \( f_2 \) shifts in horizontal direction from 10.5 GHz to 11.5 GHz. Therefore, the width of the \( W_3 \) in the stepped impedance filter affects its frequency range of selection at high frequencies. Fig. 8(b) shows the effect of \( W_4 \) on shape factor \( K \), with the decrease of the \( W_4 \), the frequency selection characteristics are improved signifi-
cantly. As shown in Fig. 8(b), the value of $K$ has changed from 1.172 to 1.038. Fig. 8(c) shows the influence of the width change of the $W_5$ in the step filter on the reflected zero point. As can be seen from the diagram, when the $W_5$ is decreased, the reflected zero becomes more and more obvious. When $W_5 = 5.2$ mm, an optimal value is obtained which meets the design requirements.

All the parameters of the proposed antenna are optimized by using commercial full-wave software CST Microwave Studio. The final dimensions of the slot antenna are as follows:

$L = 24$ mm, $L_1 = 15$ mm, $L_2 = 4.2$ mm, $L_3 = 5.4$ mm, $L_4 = 2$ mm, $L_5 = 0.7$ mm, $L_6 = 1.6$ mm, $L_7 = 2.4$ mm, $L_8 = 2$ mm, $L_9 = 14.2$ mm, $L_{10} = 2$ mm, $L_{11} = 9.4$ mm, $W = 12$ mm, $W_1 = 8.1$ mm, $W_2 = 8.5$ mm, $W_3 = 0.4$ mm, $W_4 = 5.4$ mm, $W_5 = 5.2$ mm, $W_6 = 2$ mm, $S_1 = 0.5$ mm, $S_2 = 0.5$ mm.

![Fig. 8](image_url)

**Fig. 8.** The width of $W_3$, $W_4$, $W_5$ effect on the reflection coefficient curve. (a) $W_3$, (b) $W_4$, (c) $W_5$.

### 3 Results and discussion

In this section, the numerical and experimental results of the proposed antenna are presented and discussed, including its reflection coefficient, radiation characteristics, gains and group delay characteristic analysis in the time domain. The proposed antenna with and without notched structure is manufactured and tested.

Fig. 9 illustrates the measured and simulated reflection coefficient with and without the notched band. Very good agreements are observed for the entire frequency range. As shown in Fig. 9(a), the measured reflection coefficient is less...
than $-10 \text{ dB}$ from 3.1 GHz to 11 GHz. The proposed antenna has very good out-of-band suppression since no other resonance frequency exists outside the desired band. The ratio of the $-3 \text{ dB}$ bandwidth to the $-10 \text{ dB}$ bandwidth is 1.038, which is very close to 1. Fig. 9(b) shows the measured and simulated reflection coefficient with the notched band. The proposed antenna has an operating frequency is from

Fig. 9. The simulated and measured reflection coefficient of the proposed antenna with and without the notched band.

Fig. 10. Measured radiation patterns of the antenna with the notched band. (a) 3.1 GHz, (b) 6.5 GHz, (c) 10 GHz.
In the frequency range of 3–11 GHz, there are two notched bands which cover the 3.3–3.7 GHz and 5–6 GHz. The ratio of the −3 dB bandwidth to the −10 dB bandwidth is 1.038. So, the notched structure has little influence on the band-edge selectivity.

The measured and simulated radiation patterns of the filtering antenna with notched band at operating frequencies of 3.1, 6.5, and 10 GHz in H-plane (yz plane) and E-plane (xz plane) are shown in Fig. 10. It is found that the H-plane patterns are...
are nearly omnidirectional, but the E-plane radiation patterns are not as good especially at 10 GHz. This is partly due to the imbalance of current distribution at high frequency.

Fig. 11 shows the measured and simulated gains of the proposed antenna. We can see that the gain at 3.1 GHz and 10 GHz is 1.1 dBi and 4.2 dBi, respectively. The proposed antenna has a stable gain in the frequency range of UWB. Sharp decreases of the antenna gain at both the band-edge frequency and the notch frequency are obtained. The experimental results verify the design has a good suppress of out-of-band and in-band unwanted signals.

Having a constant group delay throughout the UWB band is another desired feature for a UWB antenna, dissatisfying that may lead to strong dispersion resulting in pulse distortion. Fig. 12 shows the simulated group delay of two antennas (notch frequency at 3.5 GHz and 5.5 GHz) with a 40 cm distance. As can be seen here, the in-band (except notch) group delay is close to 1.2 ns with small (within ±0.5 ns) variations. This confirms that the proposed antenna is suitable for UWB communication. Table II lists the comparison with other prior UWB antennas. It shows the advantages in size and band edge selectivity characteristics of the proposed antenna.

4 Conclusion

In this study, a novel slot UWB antenna with filtering function and notched function is proposed. By using a stepped impedance resonator as feeding line and adding narrow slot near the stepped slot, the band-edge selectivity of the proposed antenna is improved, and the out-of-band interference is suppressed. For the in-band interference suppression, two microstrip lines parallel to the feed microstrip line are used. The notch structure design is simple and convenient to implement. Additionally, the size of the antenna is smaller than most of the other slot antennas. The measured results agreed very well with simulation. Good radiation patterns and reflection coefficient characteristics confirmed the proposed antenna to be a good candidate for UWB applications.

Acknowledgments

This work was supported in part by Key research and development plan of Shaanxi Province (2017ZDXM-GY-117), Xi’an Science and Technology Plan Project (2017080CG/RC043(XALG014), (2017080CG/RC043(XALG013)), (2017080CG/RC043(XALG032)).