Compact Planar Super-Wideband Monopole Antenna with Four Notched Bands

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Abstract: A compact-sized planar super-wideband (SWB) monopole antenna with four notched bands is presented in this paper. The antenna consists of a rectangular ground plane and a circular radiator that is fed by a tapered microstrip feed line. The overall size of the antenna is 18 mm × 12 mm × 0.5 mm, and its impedance bandwidth (S11 ≤ –10 dB) ranges from 2.5 GHz to 40 GHz (bandwidth ratio of 16:1). Four notched bands are obtained using two inverted U-shaped slots, a split-ring resonator (SRR), and a meandered slot. The notched frequency bands can be adjustable by changing the parameters of parasitic slot elements, and the realized notched bands in this paper are Wi-MAX band (3.5 GHz), WLAN band (5.5 GHz), satellite communication X-band (7.5 GHz), and amateur radio band (10.5 GHz). The simulated and experimental results show good agreement with each other. The antenna possesses a high gain, super-wide impedance bandwidth, and omni-directional radiation patterns.

Keywords: compact; monopole; notched-band; planar; super-wideband

1. Introduction

Recently, ultra-wideband (UWB) systems have attracted the attention of researchers, due to their high data transmission rate and low power consumption [1,2]. According to the regulations defined by the Federal Communications Commission (FCC), a frequency range of 3.1–10.6 GHz was allocated for UWB systems [3]. Though UWB antennas cover a wide frequency range, still, they cannot be used for high-speed long-range applications. UWB antennas are mainly preferred for indoor communications, due to their limited transmission power [4,5]. The limitations of the UWB antennas can be overcome by super-wideband (SWB) antennas, which work well even with single device communication systems. The SWB antennas are characterized by a bandwidth ratio of 10:1 or higher [6]. The SWB antenna supports both short-range and long-range communication systems, and therefore serves as a potential candidate for wireless personal area networks (WPANs). SWB could be used for screening, sensing, and to provide high-resolution images required by the modern sensors. It can also be useful for radar imaging and real-time monitoring systems. SWB provides the advantage of high-speed audio/video transmission with enhanced channel capacity [7,8].

In the literature, several antenna structures have been reported for SWB applications [9–16]. In [9], the authors proposed a microstrip line-fed modified rectangular-shaped SWB antenna with an elliptical ground surface, where two stubs were used to obtain a bandwidth ratio of 14.6:1. A crescent-shaped radiating patch SWB antenna was reported with a bandwidth ratio of 11.6:1 [10]. In [11], a triangular Sierpinski geometry with a truncated ground plane and semi-circular patches on either side of the radiator was proposed, where a bandwidth ratio of 15.5:1 and maximum gain of 5.5 dBi were achieved.
A microstrip line-fed star-shaped fractal antenna design with the semi-elliptical ground surface was presented [12], where the bandwidth ratio of 11.3:1 was obtained. In Reference [13], a truncated circular-shaped monopole antenna, loaded with an elliptical slot in its center, was proposed to obtain a bandwidth ratio of 11:1. A coplanar waveguide (CPW)-fed square-shaped antenna loaded with two stubs on either side of the radiator was presented [14] with a bandwidth ratio of 14.5:1. An S-shaped SWB monopole antenna with defected ground structure (DGS) and bandwidth ratio of 13.3:1 was proposed [15]. In Reference [16], a microstrip line-fed asymmetrical rectangular patch antenna loaded with U-slots and triangular slits was reported with a bandwidth ratio of 13.5:1. The above-reported antennas suffer from the disadvantage of large size, which limits their applications into portable RF devices. The compact size antennas can be easily incorporated into miniaturized wireless systems and RF devices used for commercial and defense applications [17].

Furthermore, due to the super-wide frequency bandwidth of the SWB antennas, they may cause interference with the surrounding wireless equipment working in the licensed frequency bands such as wireless local area network (WLAN), worldwide interoperability for microwave access (Wi-MAX), amateur radio bands, and so forth [18,19]. The notch bands introduced in the wideband spectra can alleviate this interference issue. Recently, a few SWB antennas with band-notched features have been reported [20–26]. In Reference [20], a microstrip line-fed octagonal ring-shaped SWB antenna with WLAN band-notched behavior was presented. A tapered microstrip line-fed SWB monopole antenna was designed in Reference [21], where a rectangular slit was introduced in the patch to reject the WLAN band. In Reference [22], a microstrip line-fed rectangular-shaped SWB antenna was proposed, where two U-shaped slots were etched in the radiator and the feed line to notch WLAN and X-band, respectively. A dual band-notched SWB antenna was presented in Reference [23], where a U-shaped parasitic element, a T-shaped stub, and a U-shaped slot were introduced in the ground plane and the radiating patch to notch Wi-MAX and satellite communication-based X-band. In Reference [24], a triple band-notched SWB antenna with U-shaped DGS and two open arc-shaped slots was reported to eliminate WLAN and X-band. A monopole SWB antenna with three notch bands was investigated in Reference [25], where elliptical and rectangular split-ring resonators (SRRs) were introduced with varactor diode to notch WLAN, Wi-MAX, and X-band. A guitar-shaped resonating patch and chamfered rectangular ground plane SWB antenna was presented in Reference [26], where RF PIN diodes based reconfigurable band-stop filters were used to eliminate Wi-MAX, WLAN, and downlink satellite system bands. However, the band-notched SWB monopole antennas available in the literature are relatively large in size with the complicated ground surface embedded with parasitic elements and stubs. Also, the reported SWB antenna structures possess one, two, or three notch band characteristics, and SWB antenna with quad-band elimination characteristics is hardly reported.

In this paper, a low-profile compact-sized SWB antenna with quad notched-band behavior is presented. The proposed SWB antenna consists of a circular monopole radiator and a rectangular-shaped ground plane. A super-wide impedance bandwidth is achieved by integrating a triangular-shaped tapered feed line with a circular patch. In order to reject WLAN (5.5 GHz) and satellite communication X-band (7.5 GHz) from the SWB antenna, two inverted U-shaped elements are introduced in the radiating patch. The Wi-MAX (3.5 GHz) and amateur radio (10.5 GHz) bands are notched by introducing a meandered slot and an SRR in the monopole radiator, respectively. The measured and simulated results confirm the quadruple notched-band behavior of the antenna. The center frequency of the notched-band can be easily tuned by changing the length of the implanted slot. The presented SWB antenna is easy to design and can be easily integrated with other RF devices due to its compact and simple geometry. The antenna offers high gain, super-wide bandwidth, and omni-directional radiation characteristics. It covers various modern communication application bands and can be used for spectrum sensing in cognitive radio systems.
2. Antenna Design

The layout of the proposed quad band-notched SWB antenna is shown in Figure 1a. The RT/Duroid 5880 substrate with thickness \( h \) of 0.5 mm, relative permittivity \( \epsilon_r \) of 2.2, and loss tangent (\( \tan \delta \)) of 0.0027 is used for the antenna. The proposed antenna consists of a circular radiating patch and a rectangular-shaped ground plane. A tapered microstrip line is integrated with the radiator to feed the antenna. Two inverted U-shaped slots are introduced in the middle portion of the circular patch to notch WLAN and satellite communication-based X-band. Further, a meandered slot and an SRR are introduced in the upper and lower portions of the radiating patch to eliminate Wi-MAX and amateur radio bands, respectively. The enlarged view with design parameters of the meandered slot are shown in Figure 1b. The antenna is designed and optimized using a 3-D electromagnetic solver (ANSYS HFSS). The design parameters of the proposed SWB antenna are listed in Table 1. The overall size of the proposed SWB antenna is 18 mm × 12 mm × 0.5 mm.

![Proposed quad band-notched super-wideband (SWB) antenna](image)

**Figure 1.** Proposed quad band-notched super-wideband (SWB) antenna: (a) schematic, (b) enlarged view of the meandered slot, (c) fabricated prototype.

**Table 1.** Dimensions of the proposed quad band-notched super-wideband (SWB) antenna.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dimension (mm)</th>
<th>Dimension (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L )</td>
<td>18</td>
<td>6</td>
</tr>
<tr>
<td>( W )</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>( a )</td>
<td>5.55</td>
<td>1.55</td>
</tr>
<tr>
<td>( l_1 )</td>
<td>6.15</td>
<td>0.75</td>
</tr>
<tr>
<td>( l_2 )</td>
<td>3.5</td>
<td>1</td>
</tr>
<tr>
<td>( l_3 )</td>
<td>5</td>
<td>2.25</td>
</tr>
<tr>
<td>( l_4 )</td>
<td>4.45</td>
<td>0.3</td>
</tr>
<tr>
<td>( l_5 )</td>
<td>8</td>
<td>0.5</td>
</tr>
<tr>
<td>( l_6 )</td>
<td>2.75</td>
<td>0.3</td>
</tr>
<tr>
<td>( l_7 )</td>
<td>1.25</td>
<td>0.4</td>
</tr>
<tr>
<td>( l_8 )</td>
<td>2.25</td>
<td>0.25</td>
</tr>
<tr>
<td>( l_9 )</td>
<td>3</td>
<td>1.5</td>
</tr>
<tr>
<td>( b_1 )</td>
<td>1.2</td>
<td>0.4</td>
</tr>
<tr>
<td>( b_2 )</td>
<td>3.9</td>
<td>0.5</td>
</tr>
</tbody>
</table>
The evolution steps of the proposed SWB antenna are presented in Figure 2. The Antenna-1, shown in Figure 2a, consists of a simple circular patch and a rectangular ground plane. A tapered microstrip line is employed between the radiating patch and the connector to match impedance for wide bandwidth. The characteristic impedance at each section of the tapered microstrip line is transformed from $100\,\Omega$ to $50\,\Omega$ by

$$
Z(z) = \begin{cases} 
Z_0 e^{2(z/L_t)^2 \ln(Z_L/Z_0)}, & 0 \leq z \leq L_t/2 \\
Z_0 e^{(4z/L_t - 2z^2/L_t^2 - 1) \ln(Z_L/Z_0)}, & L_t/2 \leq z \leq L_t
\end{cases}
$$

(1)

where $L_t$ is the length of the taper, and $Z_L$ and $Z_0$ are the corresponding load and characteristic line impedances. The reflection coefficients of the proposed SWB antenna are shown in Figure 3a,b. The Antenna-1 offers ($S_{11} \leq -10\,\text{dB}$) an impedance bandwidth of 2.5–40 GHz.

In order to generate band-stop characteristics for the amateur radio band, an SRR is introduced in the lower region of the monopole radiator, as shown in Figure 2b. The length ($L_S$) of the SRR is calculated as

$$
L_S = (b_1 + 2l_2 + b_2 + w_2) \approx 0.5\lambda_{gi}
$$

(2)

$$
\lambda_{gi} = \frac{c}{f_{ri}} \left( \frac{1}{\sqrt{\varepsilon_{\text{reff}}}} \right)
$$

(3)

$$
\varepsilon_{\text{reff}} = \left( \frac{\varepsilon_r + 1}{2} \right) + \frac{\varepsilon_r - 1}{2} \left( 1 + \frac{12h}{0.5\pi a_{\text{eff}}} \right)^{-1/2}
$$

(4)

$$
a_{\text{eff}} = a\left[ 1 + \frac{2h}{\pi \varepsilon_r d} \ln\left( \frac{a}{2h} \right) + 1.41 \varepsilon_r + 1.77 + \frac{h}{a} (0.268 \varepsilon_r + 1.65) \right]^{1/2}
$$

(5)

where $f_{ri}$ and $\lambda_{gi}$ are the corresponding center frequency and guided wavelength of the rejected band, $a$ is the radius of the circular patch, $h$ is the thickness of the substrate, $\varepsilon_{\text{reff}}$ is the effective relative permittivity of the dielectric substrate, and $c$ is the velocity of light in free space. Similarly, as shown in Figure 2c, the interfering satellite communication X-band is notched using an inverted U-shaped slot. The length ($L_{Ui}$) of the introduced U-shaped slot is estimated as

$$
L_{Ui} = (2l_3 + b_3 + w_3) \approx 0.5\lambda_{gi}
$$

(6)

Further, the interfering WLAN band is eliminated by introducing another inverted U-shaped slot at the center region of the circular patch, as shown in Figure 2d. The length ($L_{Uo}$) of the U-shaped slot is calculated as

$$
L_{Uo} = (2l_4 + b_4 + w_4) \approx 0.5\lambda_{gi}
$$

(7)

The interfering Wi-MAX band is rejected by forming a meandered slot in the upper region of the circular disc, as shown in Figure 2e. The length ($L_M$) of the meandered slot is estimated as

$$
L_M = (l_5 + 2b_5 + 2l_6 + 2b_6 + 2l_7 + 2b_7 + 2l_8 + 2b_8 + 2l_9 + w_5) \approx 0.5\lambda_{gi}
$$

(8)

By introducing a meandered slot, two U-shaped slots, and SRR in the presented SWB monopole antenna, four notched bands are obtained at the frequencies 3.5 GHz, 5.5 GHz, 7.5 GHz, and 10.5 GHz, respectively. The calculated lengths of the notching elements are optimized to notch the entire Wi-MAX, WLAN, amateur radio, and satellite communication bands.
Figure 2. Design steps of the proposed quad band-notched SWB antenna: (a) Antenna-1; (b) Antenna-2; (c) Antenna-3; (d) Antenna-4; (e) Antenna-5.

The reflection coefficient curves in Figure 3a illustrate the behavior of Antenna-1, -2, and -3, whereas the curves in Figure 3b display the behavior of Antenna-4 and -5. In the SWB range, a single notch band (at 10.5 GHz) is obtained in the case of Antenna-2, while dual notch bands (at 10.5 GHz and 7.5 GHz) are noticed in the Antenna-3.

Similarly, by loading three notching elements in the circular disc, three notch frequencies (at 10.5 GHz, 7.5 GHz, and 5.5 GHz) are achieved in the Antenna-4. In the same way, four elements are loaded in the Antenna-5 to notch four frequencies (at 10.5 GHz, 7.5 GHz, 5.5 GHz, and 3.5 GHz). The notch frequency can be controlled by varying the dimensions of the slot/resonator.

Figure 3. Cont.
Figure 3. $S_{11}$ of the proposed antenna design steps: (a) Antenna-1 to -3; (b) Antenna-4 to -5.

Figure 4 illustrates the matching performance of the proposed SWB Antenna-1. The deviations in the real/imaginary values of the input impedance provide an approximate characteristic impedance of the feeding connector, which illustrates a good matching among them.

Figure 4. Input impedance of the SWB antenna.

Four notch elements are formed in the proposed antenna patch to remove interfering frequencies from the SWB. Figure 5 displays the surface current distribution on the proposed antenna at notch frequencies. It is noticed that the current is mainly concentrated around the SRR, inverted U-shaped slots, and meandered slot. As compared with the current direction on the radiator patch, the current around the notching element flows in the opposite direction at notch frequency. As the current is out-of-phase and flows in the opposite direction, it shows strong attenuation and cancellation of the radiating field.
Parametric Studies of Antenna Performance

The effects of the ground plane length, U-shaped slots, meandered slot, and SRR on the proposed antenna are studied.

The gap between the ground plane and the radiating element is mainly responsible for impedance matching. Figure 6 shows the simulated reflection coefficients of the proposed SWB antenna when the ground plane length \( l_1 \) is varied. The length \( l_1 \) is varied from 5.65 mm to 6.65 mm, while the other dimensions of the antenna are kept fixed. When the length \( l_1 \) is increased or decreased, the impedance matching becomes poorer in the higher frequency bands. On the other hand, when \( l_1 \) is increased to 6.65 mm, the antenna shows resonance only for the UWB range. However, a longer ground plane results in a long feed line, which increases the size of the antenna.

To study further the behavior of the notch bands, a parametric analysis on the length of the U-shaped slots, meandered slot, and SRR is performed, as illustrated in Figure 7. In Figure 7a, the changes of the reflection coefficients as varying the SRR length \( b_1 \) are shown. It is noticed that as the value of \( b_1 \) increases, the notch band moves towards the lower frequency side. Whereas, when the length of the SRR is decreased, the notch band shifts towards the higher frequency side.
Figure 6. Simulated reflection coefficients of the antenna when the ground plane length \( l_1 \) is varied.

Figure 7. Cont.

(a) Changes of the reflection coefficients as varying the SRR length \( b_1 \) are shown. It is noticed that as the value of \( b_1 \) increases, the notch band moves towards the lower frequency side. Whereas, when the length of the SRR is decreased, the notch band shifts towards the higher frequency side.

(b)
Figure 7. Simulated reflection coefficients of the antenna: (a) when $b_1$ is varied, (b) when $l_3$ is varied, (c) when $l_4$ is varied, (d) when $l_9$ is varied.

In Figure 7b,c, the variations of the reflection coefficients of the U-slot lengths ($l_3$ and $l_4$) are shown. It is observed that as the value of $l_3$ increases from 4.6 mm to 5.2 mm, the center frequency of the notch band shifts towards the lower frequency range. In the same way, the notch band shifts towards the lower frequency range, when the length $l_4$ of the larger U-slot varies from 4.05 mm to 4.65 mm. Hence, the center frequency of the notch band can be easily tuned by changing the length of the U-shaped slot. The effect of varying the length ($l_9$) of the meandered slot is shown in Figure 7d. On varying the length $l_9$ from 2.6 mm to 3.2 mm, the notch center frequency shifts towards the lower side. Considering, the available patch space and the required notch band frequencies, the optimized values are chosen for designing the proposed antenna.

3. Results and Discussion

The fabricated prototype of the proposed quadruple notched-band SWB antenna is displayed in Figure 1c. A tapered feed line is used to excite the antenna and to provide better impedance matching. Figure 8 displays the measured and simulated reflection coefficient curves of the proposed antenna. The antenna covers a wide frequency range from 2.5–40 GHz. In the resonating frequency band,
four notched bands (at 3.5 GHz, 5.5 GHz, 7.5 GHz, and 10.5 GHz) are achieved to remove interfering frequencies from the SWB. The notched frequency bands can be controlled by varying the lengths of the slots. This simulated and measured reflection coefficient curves show reasonably good agreement between them.

Figure 8. Reflection coefficients of the proposed quad band-notched SWB antenna.

Figure 9 shows the measured and simulated plots of the antenna gain. The simulated peak gain of the presented quad-notched band antenna is 7 dBi. The gain steadily increases from 2.5 GHz to 15 GHz, and remains almost constant up to 40 GHz. It is also observed that the gain sharply falls in the vicinity of the notched bands.

Figure 9. Gain of the proposed quad band-notched SWB antenna.

The simulated efficiency curve of the proposed quadruple notched-band antenna is depicted in Figure 10a. The efficiency is more than 90% in the passband region and it decreases sharply at the rejection bands. The group delay is an important parameter used to characterize the degree of distortion of the pulse signal [30]. Figure 10b shows the simulated group delay of the proposed
 quadruple notched-band antenna. The group delay curve is stable over the SWB range except at four rejection bands.

![Figure 10. Proposed quadruple band-notched SWB antenna: (a) efficiency, (b) group delay.](image)

The co-polar and cross-polar patterns of the proposed SWB antenna are shown in Figure 11. It is noticed that omni-directional co-polar radiation patterns are obtained in the H-plane, while bi-directional patterns in the E-plane. Furthermore, the cross-polarization level is lesser than the co-polarization level in both the E- and H-planes.

![Figure 11. Cont.](image)
A comparison of the proposed quad notched-band antenna with the recently reported SWB antenna designs is shown in Table 2. The antennas presented in References [9–16] did not have band rejection features. The elimination of unwanted frequency bands improves the quality of communication. The SWB antennas in References [20,21] rejected only one frequency band, while the antennas in References [22,23] rejected two frequency bands. The antenna designs in References [24–26] showed triple-band rejection characteristics. However, the drawbacks of these notched band antennas were their poor selectivity and complicated ground planes embedded with parasitic elements and stubs. Furthermore, the sizes of the SWB antennas in References [9,11,13–15,22,24,25] were quite large, which may limit their applications in monolithic microwave integrated circuits and portable high-frequency devices. The radiating patch designs in References [11,12,26] were practically complex, due to the fractal shape and integrated active elements. Furthermore, most of the SWB antennas proposed in the literature were printed on the FR-4 substrate, which is a lossy substrate and exhibits poor performance at high frequency. In the proposed antenna design, the four notched bands are obtained without using any filter/active elements, thus simplifying the antenna design process. The total area occupied by the proposed SWB antenna is comparatively small, and it can be easily integrated into portable RF devices. Thus, the proposed antenna outperforms the reported SWB antennas in terms of bandwidth ratio, simple design, compact size, and the number of notch bands.

Table 2. Comparison between the proposed quad notched-band SWB antenna and previous works related to the SWB antenna.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Antenna Size (mm × mm × mm)</th>
<th>Resonating Band (GHz)</th>
<th>Impedance Bandwidth (GHz)</th>
<th>Bandwidth Ratio</th>
<th>Number of Notch Bands</th>
<th>Notch Band Center Frequency (GHz)</th>
<th>Peak Gain (dB)</th>
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<td>[9]</td>
<td>52 × 42 × 1.575</td>
<td>0.96–13.98</td>
<td>13.02</td>
<td>14.6:1</td>
<td>-</td>
<td>-</td>
<td>5.5</td>
</tr>
<tr>
<td>[10]</td>
<td>32 × 22 × 1.6</td>
<td>2.5–29</td>
<td>26.5</td>
<td>11.6</td>
<td>-</td>
<td>-</td>
<td>6</td>
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<tr>
<td>[12]</td>
<td>19.7 × 19 × 1.6</td>
<td>4.6–52</td>
<td>47.4</td>
<td>11.3:1</td>
<td>-</td>
<td>-</td>
<td>14</td>
</tr>
<tr>
<td>[14]</td>
<td>52 × 46 × 1.6</td>
<td>0.95–13.8</td>
<td>12.85</td>
<td>14.5:1</td>
<td>-</td>
<td>-</td>
<td>6</td>
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<tr>
<td>[15]</td>
<td>35 × 35 × 1.37</td>
<td>3.08–40.9</td>
<td>37.82</td>
<td>15.3:1</td>
<td>-</td>
<td>-</td>
<td>5.9</td>
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<tr>
<td>[16]</td>
<td>25 × 26 × 1.16</td>
<td>2.43–32.93</td>
<td>30.5</td>
<td>13.5:1</td>
<td>-</td>
<td>-</td>
<td>7.35</td>
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<td>[20]</td>
<td>30 × 30 × 1.6</td>
<td>2.39–40</td>
<td>37.61</td>
<td>16.7:1</td>
<td>1</td>
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<td>[21]</td>
<td>30 × 30 × 1.6</td>
<td>3–50</td>
<td>47</td>
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<td>[22]</td>
<td>35 × 30 × 1.6</td>
<td>3.2–40</td>
<td>36.8</td>
<td>12.5:1</td>
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<tr>
<td>[23]</td>
<td>30 × 24 × 0.787</td>
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<td>23.4</td>
<td>15.6:1</td>
<td>2</td>
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<tr>
<td>[24]</td>
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<td>34.1</td>
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<td>16.1</td>
<td>4</td>
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</table>
4. Conclusions

A compact SWB monopole antenna with quadruple notched-band characteristics is presented. The antenna radiator is fed using a tapered feed line for broadband impedance matching. Four notch bands are introduced in the proposed SWB antenna to eliminate the interfering radiations of WLAN (5.5 GHz), Wi-MAX (3.5 GHz), satellite communication X-band (7.5 GHz), and amateur radio (10.5 GHz) band. The interference of WLAN and satellite communication bands are notched using inverted U-shaped slots, while the Wi-MAX and amateur radio bands are notched through a meandered slot and an SRR, respectively. The presented antenna has a simple design, without any active components on the patch or the ground plane. The proposed wide bandwidth antenna can be used for a variety of applications such as cognitive radios spectrum sensing, defense systems, doppler navigation, personal communication, radio astronomy, and so forth.


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Conflicts of Interest: The authors declare no conflict of interest.

References


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