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DESIGN AND ANALYSIS OF PLANAR ULTRA-WIDEBAND ANTENNA WITH DUAL BAND-NOTCHED FUNCTION

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Abstract—A novel planar ultra-wideband (UWB) antenna with dual band-notched characteristics is proposed. The antenna is fabricated on a printed circuit board (PCB), having a circular monopole and arc-shaped parasitic strips on one side and a ground plane with a slot aperture on the other side. Two narrow bands at 5.15–5.35 GHz and 5.725–5.825 GHz are notched by using two arc-shaped parasitic strips on the same layer of the radiator. Compared with other band-notched UWB antennas, the proposed antenna exhibits the advantages of simple structure, compact size, simple control of each notched frequency band using separate parasitic strips, and good performance. Surface current distributions and equivalent circuit model are applied to analyze the operating principle of the proposed antenna. To validate the concept, a prototype is fabricated and tested. Both simulated and measured results confirm that the proposed antenna achieves a wide bandwidth from 3.1 GHz to 10.6 GHz with two narrow bands notched successfully. The results of VSWR, radiation patterns and gain response are shown and discussed in detail. The antenna enables the independent control of the notched frequency bands, and the proposed method can be extended for designing planar UWB antennas with multiple band-notched characteristics and reconfigurable notched frequency.

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1. INTRODUCTION

The Federal Communications Commission (FCC) has allocated the frequency band from 3.1 GHz to 10.6 GHz for applications in UWB short-range wireless communication [1]. UWB systems have many advantages such as high speed data rate, extremely low emission power, low complexity and resistance to the multipath phenomenon. One of the critical issues for UWB systems is the design of UWB antenna which requires good return loss across a wide bandwidth (3.1–10.6 GHz), stable radiation patterns, compact size and low fabrication cost. In addition, the antenna is required to reject two narrow frequency bands, i.e., 5.15–5.35 GHz and 5.725–5.825 GHz, for avoiding the interference with existing wireless local area network (WLAN) (IEEE802.11a and HIPERLAN/2) [2].

An overview of planar wideband antennas with different configurations is presented in [3]. Among various types of planar UWB antennas in the literature, microstrip line or coplanar waveguide (CPW) fed slot antennas are promising candidates for UWB applications [4–9]. The advantages of such slot antennas include wideband impedance matching, stable radiation patterns, and easy integration with RF circuitry and other systems. Also the antenna has low cost as it can be fabricated easily by using the PCB technology.

To achieve the band-notched characteristics, various techniques have been proposed in [10–24]. One popular method is to embed slots or slits on the patch or on the ground plane, i.e., arc-shaped slit [13], meandered-shaped slot [14], inverted U-slot [15], and C-shaped slot [16]. Another technique to achieve the frequency band-notched function is to add parasitic elements [17–19]. A slot-type split ring resonator (SRR) [20] has been etched on the patch to obtain good performance. In [21], a couple of open end slits have been etched on the ground plane to reject a certain-frequency band. In [22], a UWB antenna with band-notched characteristics has been realized by using a tuning stub. A UWB antenna with a folded strip to generate a notched band has been proposed in [23]. In addition, a simple microstrip line fed patch antenna has been presented to achieve the band-notched function by connecting an extra patch with the feed line through via [24].

However, the designs mentioned above mainly focus on the single band-notched characteristic. Several dual/multiple band-notched UWB antennas have been reported [25–27]. In [25], a multi-band notched antenna has been realized by embedding multiple slots on the patch. The disadvantage of using embedded slots within the radiator is, however, the negative impact on the gain of the antenna [26]. In [26], a couple of printed parasitic elements with tapered ends have been utilized to achieve triple band-notched function. However, this design has occupied a notch that is too wideband and reaches almost 2 GHz in each band. The required band-notches are 0.2 GHz for lower WLAN and 0.1 GHz for upper WLAN. In [27], two parasitic strips are printed near a fork-shaped radiator to achieve UWB performance with dual bands notched. As the radiator uses a "U" shape rather than a rectangular patch, gain performance of the antenna have deteriorated. Thus it is still a challenging task to design UWB antenna with multiple narrow notched bands without compromising the performance of the antenna.

Another challenge for the dual or multi-band notched antenna is the mutual coupling among each slot [25] or between two parasitic strips [27] due to the limited space available within the antenna, especially when two notched frequencies are located closely to each other. Such mutual coupling may lead to a more complicated design procedure and requiring tedious time for achieving antenna design goals. For UWB systems, it is necessary to investigate novel UWB antennas with dual or multiple band-notched characteristics which are small in size, planar and simple to design, and can achieve good performance (gain, bandwidth, radiation patterns and independent tuning of each notched band).

In this paper, a novel planar UWB antenna with dual band-notched function is proposed. Two narrow frequency bands to be notched are centered at 5.28 GHz and 5.78 GHz, respectively. The results of VSWR, radiation patterns and gain over the entire UWB band are fully examined. Compared with other dual band-notched UWB antennas [25, 27], the proposed antenna has the advantages of simple design and easy tuning at each notched frequency, since there is very low mutual coupling between two strips and the distance of separated strips isn't limited by the size of the patch.

2. ANTENNA STRUCTURE AND DESIGN

The configuration and geometry of the proposed UWB antenna with dual band-notched function is shown in Figure 1, with the yz-plane and xz-plane referred to as the E- and H-plane, respectively. In the microstrip fed slot antenna, a circular slot aperture with a radius of R_1 is etched from the rectangular ground plane. The circular radiator is fed by a $50\,\Omega$ microstrip line. The antenna is fabricated on a RT6010 substrate with a dielectric constant of 10.2 and a thickness of 0.635 mm. Two arc-shaped parasitic strips play a vital role as band-stop filters to reject two desired frequency bands. Strip one is close to the circular slot, and strip two is near the circular radiator. They can be simply

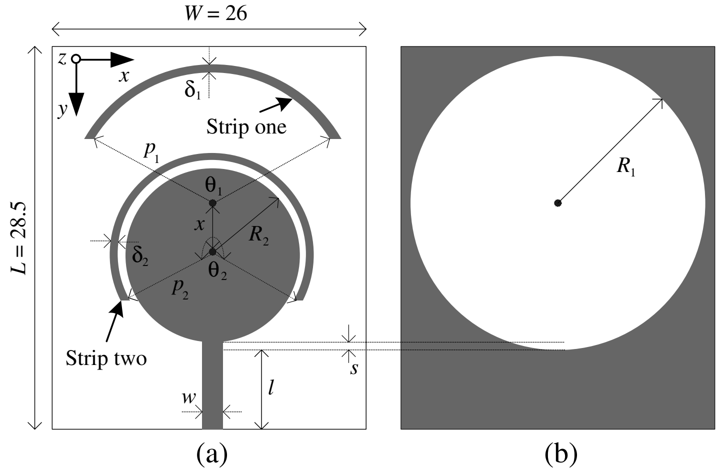

Figure 1. The configuration of the dual band-notched UWB antenna. (a) Top layer. (b) Bottom layer.

adjusted and their dimensions aren't limited by the exterior size of the circular radiator. The radius, angle, and width of the parasitic strips are denoted as p_i, θ_i, δ_i, (where $i = 1, 2$), respectively.

The design steps of the dual band-notched UWB antenna are summarized as follows.

Firstly, the lowest operating frequency of this antenna is predicted by evaluating the radius of the slot aperture (R_1) and the circular monopole (R_2). This can be done by implementing the following approximate equations:

$$R_1 \approx \frac{c}{4f_1\sqrt{\frac{1+\varepsilon_r}{2}}} \tag{1}$$

$$R_2 \approx \frac{R_1}{2} \tag{2}$$

where c is the speed of light in free space, ε_r is the dielectric constant of the substrate and f_1 is the lowest operating frequency.

Secondly, values of s and x are chosen to achieve the required impedance matching. Parametric study concerning the choice of the best value of s indicates that it should not be larger than the thickness of the substrate in order to get the largest operational bandwidth [20].

Thirdly, the rejected frequencies are realized by adding two arc-shaped parasitic strips. The dimensions can be chosen according to the following formulas:

$$f_{\text{notch},i} \approx \frac{c}{l_{\text{arc},i}\sqrt{\frac{1+\varepsilon_r}{2}}} \tag{3}$$

$$l_{\text{arc},i} = \frac{\theta_i}{360^\circ} \times 2\pi p_i \tag{4}$$

where $l_{\text{arc},i}$ ($i = 1, 2$) are the effective lengths of the parasitic strips.

The initial values of antenna dimensions assuming $f_1 = 3.1\,\text{GHz}$, $f_{\text{notch},1} = 5.2\,\text{GHz}$ and $f_{\text{notch},2} = 5.8\,\text{GHz}$ are as follows: $L = 28.5\,\text{mm}$, $W = 26\,\text{mm}$, $w = 0.6\,\text{mm}$, $l = 4.5\,\text{mm}$, $R_1 = 11\,\text{mm}$, $R_2 = 5.2\,\text{mm}$, $x = 5\,\text{mm}$, $p_1 = 10\,\text{mm}$, $\theta_1 = 143^\circ$, $p_2 = 5.6\,\text{mm}$, $\theta_2 = 240^\circ$, $\delta_1 = \delta_2 = 0.22\,\text{mm}$.

Finally, full-wave EM simulator (HFSS) is employed to further optimize the parameters based on the initial results.

The formulas to calculate the notched frequency are validated by comparing the calculated results and simulated results from HFSS, as shown in Figures 2 and 3. The radius and angle of strip one will be varied while holding other parameters with the dimensions presented as aforementioned. Figure 2 shows the comparison between calculated and HFSS results of the notched frequency for various strip radii when the angle is fixed at 143°. It can be seen that the maximum discrepancy reaches about 0.2 GHz in the upper band. Figure 3 exhibits the comparison between the calculated and simulated values of the rejected frequencies for different arc angles when the radius is fixed at 10 mm. As can be noticed, the difference between the calculated and HFSS results keeps constant and it is found to be less than 0.15 GHz. The

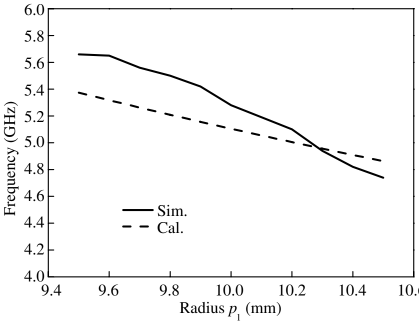

Figure 2. Comparison between the calculated and simulated values of the notched frequency for various strip radii.

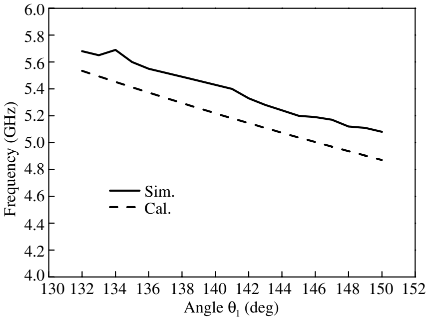

Figure 3. Comparison between the calculated and simulated values of the notched frequency for various arc angles.

formulas listed above can be employed to calculate the dimensions of the arc-shaped parasitic strips approximately.

3. SIMULATED AND MEASURED RESULTS

In order to validate the design of the proposed antenna, a prototype has been fabricated and tested. The results of simulated and measured VSWR are shown in Figure 4. Both results confirm that the proposed antenna achieves a bandwidth from 3.1 GHz to 10.6 GHz for VSWR $\leq$ 2, in which two frequency bands in 5.04–5.39 GHz and 5.62–5.93 GHz for VSWR $\geq$ 2.5 are notched successfully. The rejected bands cover the desired frequency bands in 5.15–5.35 GHz and 5.725–5.825 GHz. The values of VSWR are larger than 10 at the notched frequencies.

The surface current distributions on the antenna at four different frequencies are shown in Figures 5(a)–(d). It is observed that, at 4 GHz and 8 GHz (outside the notched band), the distribution of the surface current is uniform and primarily concentrated near the periphery of the circular radiator and the slot. While at 5.28 GHz and 5.78 GHz, the energy is strongly coupled to strip one and strip two, respectively, causing the notched bands. It is worthwhile to mention that, there is low mutual coupling at two rejected frequencies indicating that each rejected frequency can be controlled independently.

The impedance of the band-notched antenna and reference antenna are compared in Figure 6. As observed, the real curve of the reference antenna is around 50 Ω which indicates good impedance matching across the whole operating frequency band. Compared with the reference antenna, the real component of the band-notched antenna reaches zero at the notched frequencies and the imaginary part exhibits series resonance characteristics. The results suggest that the inclusion

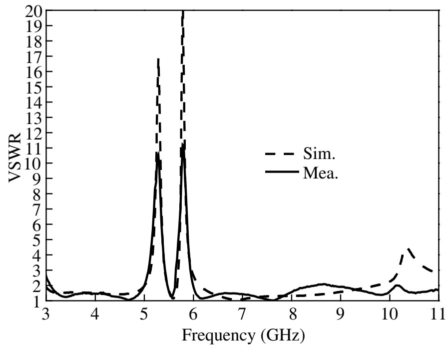

Figure 4. Simulated and measured VSWR versus frequency.

of the parasitic strips causes the antenna nonresponsive at the rejected frequencies.

Figure 7 displays the equivalent circuit model of the dual band-

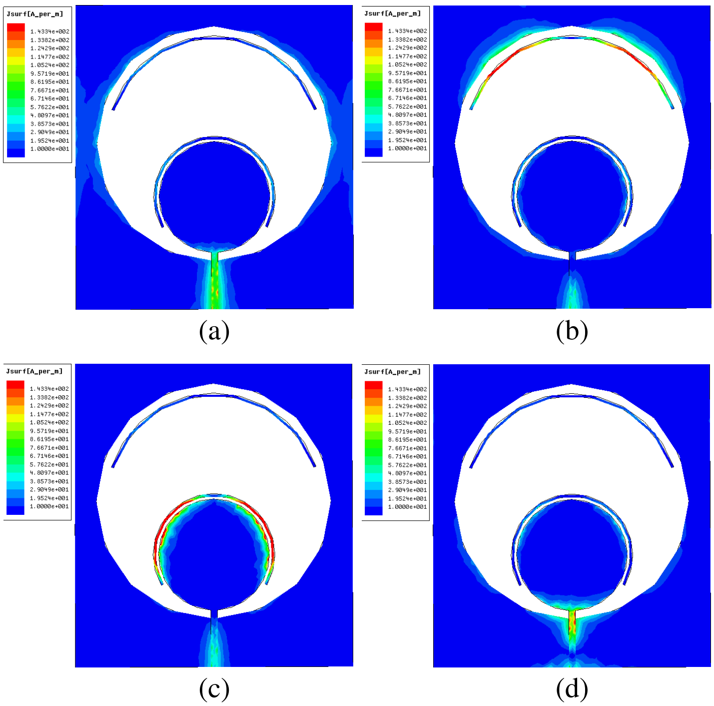

Figure 5. Surface current distributions at different frequencies. (a) 4 GHz, (b) 5.28 GHz, (c) 5.78 GHz, and (d) 8 GHz.

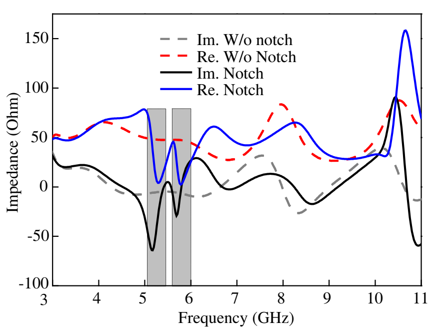

Figure 6. Comparison of the impedance for the band-notched antenna and reference antenna.

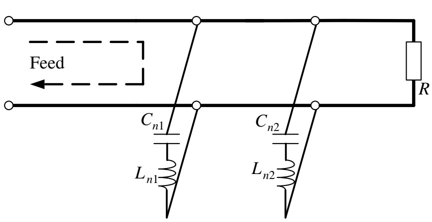

Figure 7. Equivalent circuit model of dual band-notched UWB antenna.

notched UWB antenna. The parasitic strip behaves as an inductor, and the gap between strip one and the circular slot works as a capacitor. A series LC-resonant circuit is connected in parallel with R equivalently. When the proposed antenna is operating at 5.28 GHz, the corresponding LC-resonant circuit mentioned above will be syntonic and the impedance approaches zero, which makes the input impedance of the antenna to be shorted. While at other pass-band frequencies, the parasitic strip has no effect. The operating principle of the proposed antenna at 5.78 GHz can be explained by the above analysis as well.

Measurements of the radiation patterns of the prototype are carried out in a far-field anechoic chamber using an elevation-over-azimuth positioner, with the elevation axis coincident with the polar axis ($\theta = 0°$) of the antenna's co-ordinate system. The azimuth drive thus generates cuts at constant ϕ. Figure 8 presents the measured radiation patterns in both E- and H-plane at 4 GHz and 8 GHz.

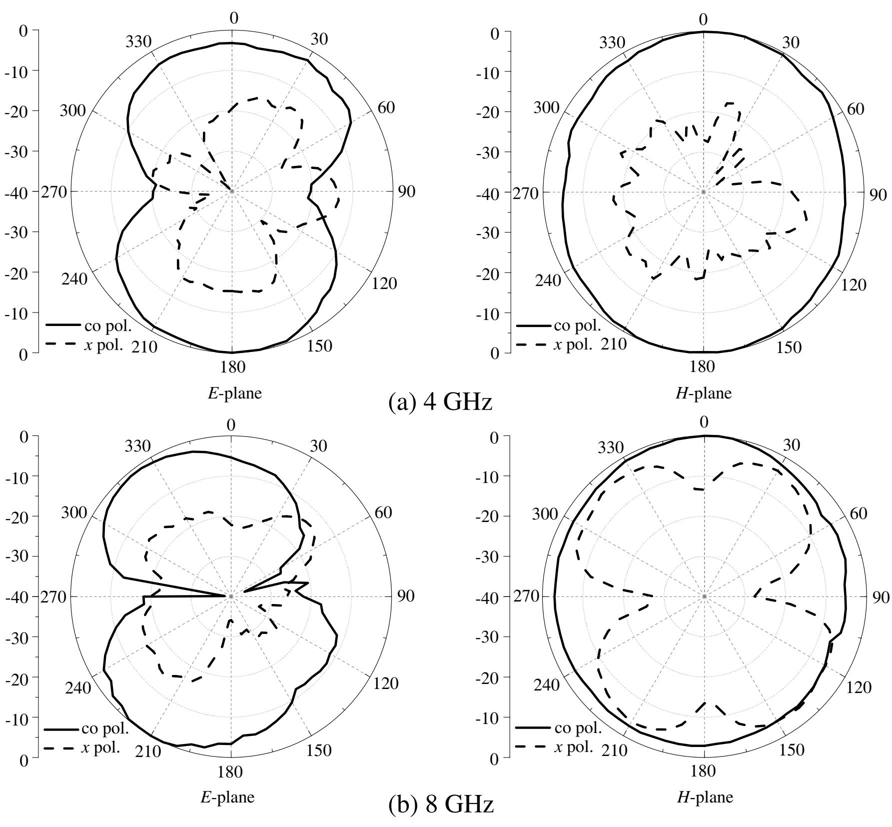

Figure 8. Measured radiation patterns at different frequencies.

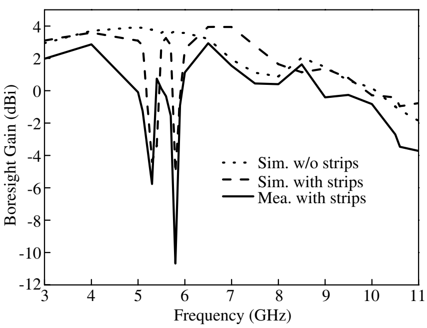

Figure 9. Measured realized antenna gain versus frequency.

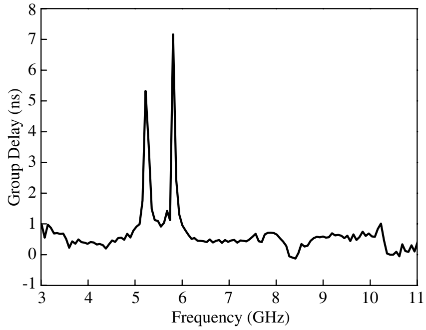

Figure 10. Measured time domain result.

It reveals doughnut shaped patterns at 4 GHz which is similar to a conventional monopole in free space. The proposed antenna exhibits omni-directional patterns in the H-plane at 4 GHz and 8 GHz. It shows bi-directional patterns in the E-plane, though the maximum direction shifts off the boresight at 8 GHz due to the high-order resonant mode [1]. The cross polarization at 8 GHz is higher in comparison to the corresponding values at 4 GHz.

Figure 9 shows the measured boresight gain versus frequency for the dual band-notched antenna alongside that of the reference antenna. As observed, a sharp gain reduction is obtained at the rejected frequencies. For other frequencies outside the notched band, the antenna gain with parasitic strips is similar to that of the reference antenna. The antenna gain is found to be −6.79 dBi at 5.28 GHz and −10.78 dBi at 5.78 GHz, which implies the effectiveness of the band-notched function of the proposed design.

The group delay of the proposed antenna is also measured by locating two identical antennas face to face and the corresponding result is shown in Figure 10. Apart from the notched bands, the group delay shows slightly small variations, indicating that the proposed design is suitable for UWB applications.

4. DISCUSSION AND COMPARISON OF THE PROPOSED BAND-NOTCHED ANTENNA AGAINST RECENT AVAILABLE PUBLISHED DESIGNS

In this study, a planar dual band-notched UWB antenna has been obtained by inserting two parasitic strips, which are printed on the same layer of the radiator. One is near the edge of the radiating patch whereas the other one is close to the circular slot. This design can provide the capability of avoiding the interferences with both the lower and higher WLAN bands by adjusting the lengths of the included parasitic strips. Some other multiple band-notched antennas have already been investigated in achieving dual or triple band-notched UWB antennas [25–36]. The band-notched performance can be characterized in terms of VSWR and gain suppression at notched frequencies. Generally, the higher of the rejection levels (VSWR and gain suppression) at notched frequencies, the better the band-notched performance of the band-notched antenna should be. The comparison of the simulated and measured VSWR at the notched frequencies between the proposed design and published designs in the literature is shown in Table 1. The designs in [27, 33, 36] have good band-notched performance at one notched frequency while limited band-notched performances at other notched frequencies. The results in [32] and [35] demonstrate acceptable band-notched performances in the

Table 1. Comparison of the proposed design with state-of-the-art designs in terms of VSWR at notched frequencies.

	This work	Ref. [25]	Ref. [27]	Ref. [28]	Ref. [29]	Ref. [30]
Sim. VSWR	17 & 20	6 & 6 & 6	10 & 4	NaN	9 & 7	8 & 8.5
Mea. VSWR	10 & 11	5 & 5 & 5	7 & 4	NaN	8 & 6	7 & 5.7
	Ref. [31]	Ref. [32]	Ref. [33]	Ref. [34]	Ref. [35]	Ref. [36]
Sim. VSWR	8 & 7	>6 & >6	10 & 6 & 5	7 & 10 & 8	5 & 5 & 5	8 & 3 & 3
Mea. VSWR	8 & 8	4 & 3	9 & 6 & 5	5 & 3 & 3	5 & 5 & 5	6 & 3 & 3

Table 2. Comparison of the proposed design with state-of-the-art designs in terms of gain suppression at notched frequencies.

	This work	Ref. [25]	Ref. [27]	Ref. [28]	Ref. [29]	Ref. [30]
Gain Supp. (dB)	10 & 15	7 & 8 & 7	8 & 5	10 & 8	6 & 6	9 & 7
	Ref. [31]	Ref. [32]	Ref. [33]	Ref. [34]	Ref. [35]	Ref. [36]
Gain Supp. (dB)	5 & 8	NaN	14 & 8 & 7	6 & 3 & 3	4 & 7 & 3	7 & 4 & 5

simulation but limited band-notched performance in the measurement due to the dielectric loss of the substrate. The VSWR of the band-notched antennas reported in [25, 29–31], and [34] is below 10 at notched frequencies. Furthermore, Table 2 demonstrates the gain suppression comparison between the proposed band-notched design and other band-notched antennas. The results in the table exhibit reasonably superior band-notched performance than most of the existing studies when comparing the gain at notched frequencies with the corresponding values at other passband frequencies.

5. CONCLUSION

A microstrip-fed UWB antenna with dual band-notched characteristics is proposed. The overall volume of the antenna is 26 mm $\times$ 28.5 mm $\times$ 0.635 mm. The dual band-notched function is achieved by adding two arc-shaped parasitic strips on the same layer of the radiator. Each notched frequency band can be independently controlled by each parasitic strip, i.e., the design of multiple band notches are easy to be achieved. The proposed antenna has advantages such as a simple structure, easy design, independent control of each notched frequency band and can avoid the interference problem for the lower and upper WLAN frequency bands. The results of VSWR, radiation patterns, and gain are shown and discussed in detail. Both simulated and measured results show that the proposed antenna achieves a wide bandwidth from 3.1 GHz to 10.6 GHz with two narrow bands notched successfully.

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