Compact antipodal Vivaldi antenna design with gain enhancement and notched-band characteristics based on D-CRLH metamaterial

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Abstract

A novel compact ultra-wide band (UWB) antipodal Vivaldi antenna with band notched is presented in this communication. T-shaped slot is introduced to extend the lower end limitation of the frequency band from 1.65 GHz to 1.25 GHz, the miniaturization of the antenna is realized. Then a new thought of the gain enhancement, namely the substrate cutout (SCO) is demonstrated to increase antenna gain, which makes the electromagnetic wave get rid of the bondage of the substrate, reducing the edge diffraction, and thus radiates more effectively, without changing the overall dimension of the antenna. The advantage is of great value in limited space especially. Then a compact unit cell based on Dual Composite Right-Left Handed (D-CRLH) metamaterial is proposed to realize the notched band characteristics in the WLAN band (4.95–5.15 GHz). In addition, the passband would be less affected by the notched band due to the sharp transition band between notched and operating band. Finally, the antenna is successfully simulated and measured, it shows broadband matched impedance, stable gain and radiation pattern over the operating band. The experimental results are also given and show a good agreement with the simulated results.

1. Introduction

The essence of radio astronomical observing technology is radio reception technology, aimed at measurement of the cosmic radio waves. Over the past few years, study of significantly improving the observing capability have received increasingly prominent consideration [1, 2]. The new observing techniques of radio astronomy started to be researched towards higher sensitive and wider field-of-view (FoV) capabilities, which is required for the study of many astronomical and cosmological phenomena. Hence, a new generation of telescopes with very large collecting areas and broad operating frequency bands is attractive for astronomical observations. Vivaldi antenna, which provides wide bandwidth, easy fabrication, and low-profile property, is attractive for the radio astronomy application [3, 4]. But it is difficult to miniaturize as its operating frequency is determined by the aperture width. Besides, the gain of the vivaldi antenna is relatively low, according to the Friis formula as follows [5],

$$F_{\text{total}} = F_1 + \frac{F_2 - 1}{G_{A1}^*} + \frac{F_3 - 1}{G_{A1}^*G_{A2}^*} + \cdots + \frac{F_n - 1}{G_{A1}^*G_{A2}^*\cdots G_{An}^*}$$  \hspace{1cm} (1)$$

The gain of the antenna contributes most to system noise $F_{\text{tot}}$. Therefore, the research about Vivaldi antenna simultaneously with miniaturization and gain enhancement has a great research significance.

On the other hand, although the vivaldi antenna could operate on the wideband, with the development of technology, the radio frequency interference (RFI) from human activities becomes increasingly prominent. It is very necessary to design the broadband antennas with band notched function to suppress radiation from interfering narrow band systems [6–10]. In [6], a novel UWB antipodal Vivaldi antenna with band-notched characteristics is achieved by placing a parasitic square split-ring resonator (SRR) near the radiating arm.
However, the designs will affect the radiation characteristics of the antenna, also the size of resonator becomes large. By properly loading some resonators on the feed section to invoke the frequency band notched is adopted in [8–10]. However, these modifications are mostly non-scalable and hence hard to calibrate and may affect the efficiency and radiation pattern of the antenna by the perturbation of the radiating elements.

To solve the problems mentioned above, a miniaturized and gain-enhancement antipodal Vivaldi antenna using D-CRLH metamaterial for band notched characteristics is proposed. The T-shaped slot is introduced on the radiator to extend the low cut-off frequency from 1.65 GHz to 1.25 GHz, without changing the overall dimension, realizing the miniaturization. The traditional methods of gain enhancement based on metamaterial [11, 12] or director [13], dielectric lens [14, 15] enlarge the dimension of the antenna, together with the loss and radiation efficiency. Here we first employed the substrate cutout (SCO) to improve the directivity together with gain in the end-fire direction, which makes the electromagnetic wave get rid of the bondage of the substrate, reducing the edge diffraction, and thus radiates more effectively. The composite right/left-handed transmission line (CRLH TL) is an applicable candidate for the design of arbitrary dual-band power divider due to its inherent dual-band performance including left-handed (LH) band with a phase advance and right-handed (RH) band with a phase delay. Besides, its sub-wavelength structure can be used to miniatu rize the semicro wave devices [16–19]. Nevertheless, the metallized vias and lumped elements lead to higher insertion loss and higher fabrication costs. Compared with the traditional methods, the proposed method makes the design more compact. Furthermore, with the help of the simulation tool shorted for ADS, the compact unit cell based on D-CRLH metamaterial with natural stop-band characteristics is designed and analyzed. Comparing D-CRLH with CRLH, the left-handed inductance (L_L) is realized by the high impedance microstrip line, without vias, which has greatly facilitated the fabrication process. After loading it on the feeding line, the antenna successfully achieves the notch band of 4.95–5.15 GHz. For demonstration, the antenna is finally fabricated and measured. Measurements verify the excellent performance of the antenna.

To the best of our knowledge, CRLH is frequently used as the pass-band filter, few works have been reported that CRLH is used as stop-band filter for notched band design. Moreover, in the traditional Vivaldi antenna design, the slot structure is used to reduce the diffraction [20–23], herein, the slot is used for miniaturization. The compact ultra-wide band (UWB) antipodal Vivaldi antenna with band notched is believed to be a good candidate for the application of radio astronomy. This paper is organized as follows. The design procedures of the Vivaldi antenna is presented in section 2. The measured results of a fabricated prototype are presented in section 3, and a brief conclusion is given in section 4.

2. Antenna design

The design evolution of the compact UWB antipodal Vivaldi antenna is proposed in figure 1. All of the antennas are implemented on the RF-35 substrate with ε_r = 3.5, loss tangent tan δ = 0.0019, thickness h = 0.78mm.

2.1. Miniaturization

The initial antenna begins with a conventional antipodal Vivaldi antenna (ANT 1). The inner (y_1) and outer (y_2) edges of the main radiator of antipodal Vivaldi antenna fit the following exponential curves. The exponential form of the radiating fins is useful for wideband matching, and the functions for the radiating fins are written as follows:

\[ y_1 = 0.5^*\left[ a_1 (e^{k_1 x_1} - 1) + W_1 \right] \quad 0 \leq x_1 \leq L_1 \]  
\[ y_2 = 0.5^*\left[ a_2 (e^{k_2 x_2} - 1) - W_1 \right] \quad 0 \leq x_2 \leq L_2 \] 

![Figure 1. The evolution of the proposed antenna (a) ANT 1 (b) ANT 2 (c) ANT 3 (d) ANT 4.](image-url)
where

\[
\begin{align*}
  k_1 &= \frac{1}{L_1} \ln \left( \frac{W + W_i + a_1}{a_1} \right) \\
  k_2 &= \frac{1}{L_2} \ln \left( \frac{W - W_i + a_2}{a_2} \right)
\end{align*}
\]

\(a_1\) and \(a_2\) are determined by the opening rate, \(W\) is the maximum opening width and \(W_i\) is minimum opening width. To miniaturize the antenna, a pair of T shaped slots is adopted to reduce the low cut-off frequency while maintaining the same dimensions (namely ANT 2). As shown in the figure 2, the lower end limitation of antenna with \(S_{11} \leq -10 \text{ dB}\) from 1.65 GHz to 1.25 GHz. To further study the mechanism of the miniaturization with T shaped slot, the surface current distributions of ANT 1 and ANT 2 at 1.3 GHz are shown in figure 3. It can be seen that the current concentrates along the microstrip arms of Antenna 1 and hardly to radiate at 1.3 GHz. In contrast, by adopting the T shaped slots, the current is directed to the edge of the tapered slot and then radiate to the free space. Obviously, the proposed T-shaped slot is is beneficial to miniaturize the size of the antenna by reducing the lower operating frequency.
2.2. Gain enhancement

In order to implement gain enhancement, the V-shaped substrate cut-out is added to the ANT 2 (namely ANT 3), as depicted in figure 1(c). As we know, the dielectric has the property of high field confinement and confines most of the energy. Based on the property, we have provided a new thought of the gain enhancement, namely the substrate cut-out (SCO), which is different from the loading dielectric technique with large dimensions [13, 14].

By introducing the V-shaped substrate cut-out, the energy can be totally free of the confinement of the substrate and radiate effectively. On the one hand, the dielectric loss is reduced. On the other hand, much more energy has radiated into the air, which means less energy would diffract along the edge, decreasing side-lobe level. The radiation patterns of ANT 2 and ANT 3 at 5.5 GHz shown in figure 4(a) have verified the analysis very well. Thus, the gain in the end-fire direction would be improved, which can be validated by the comparison of gain variation versus frequency of ANT 2 and ANT 3 presented in figure 4(b).

To better guidance the design, we have investigated the effects of parameters $S_h$ (height) and $S_w$ (width) of V-shaped substrate cut-out on the gain of the proposed antenna shown in figures 5(a) and (b). Obviously, both of $S_h$ and $S_w$ will strongly influence the gain of the antenna, especially in higher frequency. And with the value of $S_h$ ($S_w$) increases, the gain is further enhanced, meaning that larger area of the substrate cutout (SCO) helps more energy to radiate, the gain is thus improved. The results shown in figures 5(c) and (d) indicate that the size of the substrate cut-out has little effect on antenna bandwidth, which further verified the proposed substrate cut-out could effectively improve the gain performance, without inhibiting the bandwidth performance.

2.3. Band-notched characteristics

ANT 4, which has employed the D-CRLH unit cell for band-notched functions to suppress interference, is shown in figure 1(d). The proposed unit is composed of the interdigital capacitor served as a parallel LC tank.
In the series branch, the high impedance microstrip line equivalent as the left-handed inductance \( L_L \) in the shunt branch and the patch capacitance as the right-handed inductance \( C_R \) in the shunt branch. To better illustrate the controlling of the notched frequencies, the equivalent circuits is displayed in figure 6. The structural parameters of the resonator is chosen as follows: \( W_3 = 0.2 \text{ mm} \), \( W_4 = 0.8 \text{ mm} \), \( L_5 = 5.7 \text{ mm} \), \( L_6 = 2.9 \text{ mm} \), \( L_7 = 2.8 \text{ mm} \), \( c_s = 0.2 \text{ mm} \). To obtain the numerical values of the capacitance and inductance in the equivalent circuit, using relations from [16]:

\[
\begin{bmatrix}
Y_{11} & Y_{12} \\
Y_{21} & Y_{22}
\end{bmatrix} =
\begin{bmatrix}
jwC_L + \frac{1}{jwL_R} + \frac{jwC_R}{1 - w^2C_R L_L} & -jwC_L + \frac{1}{jwL_R} \\
-jwC_L + \frac{1}{jwL_R} & jwC_L + \frac{1}{jwL_R} + \frac{jwC_R}{1 - w^2C_R L_L}
\end{bmatrix}
\]

(4)

\[
L_R = \frac{2}{j\omega} \left( -Y_{12} + \omega \frac{\partial Y_{12}}{\partial \omega} \right)^{-1}
\]

(5)

\[
C_L = \frac{1}{2j\omega} \left( -Y_{12} - \omega \frac{\partial Y_{12}}{\partial \omega} \right)
\]

(6)

\[
C_R = \frac{-2}{j\omega} \left( \omega \frac{\partial(Y_{11} + Y_{12})}{\partial \omega} - \frac{1}{Y_{11} + Y_{12}} \right)^{-1}
\]

(7)
\[
L_L = \frac{1}{2j\omega} \left( \frac{\partial(Y_{11} + Y_{12})^{-1}}{\partial\omega} + \frac{1}{Y_{11} + Y_{12}} \right)
\]  

(8)

where \(\omega\) is the angular frequency, and \(Y_{11}, Y_{12}, Y_{21},\) and \(Y_{22}\) are of the admittance matrix. And the numerical values of the equivalent circuit are listed as follows: \(L_R = 6.91\) nH, \(C_L = 0.142\) pF, \(L_L = 1.54\) nH, \(C_R = 0.014\) pF. According to the equivalent circuit, the D-CRLH structure can produce two resonance of shunt resonance and series resonance, corresponding to the right-handed (RH) and left-handed (LH) responses at low/high frequency bands, respectively. Figure 7 illustrates the simulated frequency response of the circuit model by ADS, its shunt resonance frequency \(f_{R}\) is about 5.1 GHz, the frequency of series resonance falls out of the operational...

Figure 8. Simulated and measured S parameter.

Figure 9. Surface current distributions of ANT4 at (a) 3GHz, (b) 5GHz and (c) 7GHz.

Figure 10. (a) 3D patterns with D-CRLH (b) 3D patterns without D-CRLH.
band (1.25 GHz–12 GHz). The in-band notched frequency is mainly calculated by the shunt resonance ($L_R \times C_L$). In this condition, the D-CRLH unit cell can be equivalent as a resonator, and the resonant frequency of the D-CRLH resonator $f_{R}$, which would be the center frequency of the notched band $f_{\text{notch}}$, can be calculated by

$$f_{\text{notch}} = f_R = 1/(2\pi \sqrt{L_R \times C_L})$$ \hspace{1cm} (9)

To verify the predictions of (8), figure 8 illustrates the simulated reflection coefficient $S_{11}$ of ANT 4. The impedance bandwidth ranges from 1.25 to 12 GHz and the notched band ($S_{11}>-10$dB) ranges from 4.95 to 5.15 GHz, which is in good agreement with the simulated results of ADS shown in figure 7. Obviously, the D-CRLH resonator causes impedance mismatching of the antenna seriously in the notched band.

To clarify the band-notched mechanism of the proposed antenna more essentially, the current distributions of Antenna 4 at 3 GHz, 5 GHz and 7 GHz are given in figure 9. It can be observed that, at 3 GHz and 7 GHz, current travels along the feedline to the edges of the tapered slot for radiation, with little current transmitted to D-CRLH resonator. While the current is mainly coupled on the D-CRLH resonator and oscillates in the resonator at 5 GHz, and the antenna can hardly radiate effectively, which can be seen more intuitively from the 3D patterns at 5 GHz shown in figure 10. The band-notched characteristic is thus achieved. Figure 11 shows the simulated gain with band notched. Obviously, the gain drops significantly in the frequency band of 4.95–5.15 GHz.

### 3. Results and discussion

Based on the above analysis, we have optimized the geometry parameters, and the optimal dimensions of the antenna are listed in table 1. The proposed compact antipodal Vivaldi antenna with D-CRLH resonator is finally fabricated and measured. The photograph of the fabricated antenna is shown in figure 12 and the measured magnitudes of the reflection coefficient are illustrated in figure 13, where the simulated ones are as reference. The measured results agree well with the simulated ones, with the notched band from 4.95 GHz to 5.15 GHz. The gain versus frequency is also presented in figure 11. Slight deviation between the simulated and measured results is caused by the dielectric loss and fabrication errors. Figure 13 shows the simulated and measured normalized radiation patterns of the proposed Vivaldi notched antenna (ANT 4) in E-plane and H-plane at

| Parameter   | Value (mm) | Parameter   | Value (mm) | Parameter   | Value (mm) |
|-------------|------------|-------------|------------|-------------|------------|
| $c_s$       | 0.2        | $W_1$       | 20         | $W_3$       | 9.1        |
| $W_2$       | 0.2        | $L_3$       | 5          | $L_4$       | 5          |
| $W_4$       | 0.8        | $L_5$       | 5.7        | $f_{\omega}$|            |
| $L_1$       | 40         | $L_6$       | 2.9        | $S_w$       | 2.8        |
| $L_2$       | 20         | $L_7$       | 2.8        | $S_h$       | 12         |
| $L_3$       | 5          | $f_{\omega}$| 1.8        |             |            |

![Figure 11](image.png)

**Figure 11.** Simulated and measured gain.
Figure 12. The prototype of the fabricated antenna of top view (left) and bottom view (right).

Figure 13. Simulated and measured E- (left) and H-plane (right) normalized radiation patterns of the proposed antenna at (a) 1.4 GHz (b) 3 GHz and (c) 6 GHz (d) 10 GHz.
1.4 GHz, 3 GHz, 6 GHz, and 10 GHz. The solid line means the result of measurement and dotted means the result of simulation respectively. As it can be observed, the antenna has an end fire radiation pattern directed in the axial direction of the slot aperture. It is obvious that the experimental results are in good agreement with the simulated results.

4. Conclusion

In this paper, a compact ultra-wide band antipodal Vivaldi antenna with gain enhancement and notched band characteristics is proposed. The step-by-step modification procedure is demonstrated as follows. Firstly, the T-shaped slot is employed to extend the lower end of frequency band limitation (the lower frequency extends to 1.25 GHz from 1.65 GHz). Then a new methodology of substrate cutout (SCO) is proposed to improve the gain in the end-fire direction. After introducing the V-shaped substrate cutout, the gain has improved by 3 dB in the end-fire direction. And the last step is to load D-CRLH resonator for notched band of 4.95–5.15 GHz. The gain in the notched band is remarkably decreased. Finally, the proposed antenna is successfully fabricated and measured, and the results are in good agreement with the simulations.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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