Research Article

Backfire Patch Antenna with Enhanced Gain and Low Side-Lobe Level under Triple-Mode Resonance

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Received 4 November 2022; Revised 15 December 2022; Accepted 23 December 2022; Published 8 February 2023

Academic Editor: Xiao Ding

A novel design approach to wideband, triple-mode resonant microstrip patch antenna with enhanced backfire gain and low side-lobe level, is advanced. The antenna consists of a 2.0-wavelength sectorial magnetic dipole and an annular sector reflector which width is an odd multiple(s) of 1/4-wavelength. Under high-order mode resonance, the principal radiator and the reflector can be tuned to electrically couple, thus simultaneously to yield enhanced backfire radiation and low side-lobe level. As is numerically simulated and experimentally validated, the width of reflector is finally determined to be 3/4-wavelength. In that fashion, the antenna exhibits an impedance bandwidth of 43.6%, with a backfire gain up to 7.3 dBi and a first side-lobe level as low as -16.4 dB in V2X-band within xy-plane.

1. Introduction

With the advent of the fifth-generation (5G) mobile communications, new development opportunities for Internet of Vehicles technologies have emerged [1]. In vehicular communication scenarios, coverage ability in the low-elevation angles (i.e., in parallel to the metallic vehicle body, as well as the ground plane) is crucial to reversing, automatic, and cooperative driving, etc. [2]. It is always challenged to enhance the radiation level in the direction parallel to the metallic vehicle body while simultaneously maintaining a low antenna profile [3]. Thus, planar backfire/endfire antennas are desirable in such applications [4, 5]. Owing to their simple structure, cost-effective and high directivity [6, 7] and backfire/endfire antennas have been widely used in wireless LAN systems, satellite navigation, V2X communications, and so on. As usual, the most classical backfire/endfire antennas are implemented based upon Yagi-Uda antennas [8–11]. Recently, a series of novel patch antennas based on similar principle have been developed [12–22], with good directivity and high gain in the backfire or endfire directions. Generally, most of microstrip Yagi-Uda antennas share a common narrow-band characteristic [12–19]. By sacrificing the low-height property in geometry, broadband characteristics can be yielded [20–22].

More recently, it has been revealed that a circular patch antenna under multimode resonance can simultaneously exhibit broadband, low profile, and enhanced backfire radiation characteristics: as is reported, the antenna exhibits an available bandwidth of 26.2%, height of 0.06 wavelength, and backfire gain up to -0.5 dBi [23]. As can be seen, using high-order mode resonance may enhance the radiation level in parallel to the metallic vehicle body [23–25]. By incorporating additional reflector/director to the high-order mode resonant principal dipole, broadband and improved
endfire/backfire gain can be simultaneously attained [24, 25]. Nevertheless, the presented design approach may also yield relatively high first side-lobe level up to -3 dB in [24] and -6 dB in [25]. Therefore, it is a big challenge to develop a low-complexity design approach to planar, high-order mode resonant antenna with low side-lobe level and high backfire directivity.

In this article, a novel design approach to triple-mode resonant patch antenna with low first side-lobe level and enhanced backfire gain is presented and validated at the V2X band [26]. As will be reported, an annular sector reflector is incorporated to a multimode resonant, 2.0-wavelength principal sectoral radiator to yield a wideband antenna with low first side-lobe level and enhanced backfire gain. Electrically coupled characteristic between the principal radiator and the reflector is revealed and then employed to yield high backfire gain, and low side-lobe level operation, such that enhanced backfire radiation up to 7.3 dB with side-lobe level lower than -15 dB could be yielded. Design guidelines for estimating the initial values of critical design parameters can be drawn accordingly. In final, the presented operation principle is numerically demonstrated and experimentally confirmed to verify the correctness and robustness of the advanced design approach.

2. Principle and Theory

In this work, the design approach begins with a triple-mode resonant circular sector patch antenna [25–28] with flared angle $\alpha$ using a prototype magnetic dipole with length $L = 2.0 \lambda$, where $\lambda$ is the wavelength at 5.5 GHz. Then, an annular sector reflector is incorporated to enhance the backfire radiation. The initial parameters of the reflector can be estimated by a six-point equivalent source model for realizing low first side-lobe level and enhanced backfire radiation. Numerical simulations are then performed by using Ansys HFSS to determine the final parameters.

2.1. Operation Principle and Basic Configuration. As shown in Figure 1, the antenna design process initiates from a center-fed prototype magnetic dipole of 2.0 wavelength [26, 28] under $TM_{3\pi/\alpha,1}$ mode resonance. The antenna is designed on an air substrate with a relative dielectric constant of $\varepsilon_r = 1.0$. Its radiation behavior should be codominated by $TM_{3\pi/\alpha,1}$, $TM_{5\pi/\alpha,1}$, and $TM_{5\pi/\alpha,1}$ modes. A pair of shorting pins and slits are used to disturb the fundamental $TM_{3\pi/\alpha,1}$ mode and the odd high-order TM $5\pi/\alpha,1$ mode, respectively, to realize a triple-mode resonant wideband-radiation characteristic [25, 27]. The radiation modes within $xy$-plane under $TM_{3\pi/\alpha,1}$, $TM_{5\pi/\alpha,1}$, and $TM_{5\pi/\alpha,1}$ triple-mode resonance can be theoretically calculated using the formula in reference [28]. With reference to [25] and Figure 1, when $\alpha = 4\pi/3$ (240°), stronger backfire characteristic can be obtained. Referring to the design formulas in [27], initial radius of the circular sector patch radiator can be set as $R_0$, the short-circuited pins with radius of 2.5 mm should be located at $(\rho_1 \pm \beta)$, and a pair of slits with length $L_y$ and width $W_s$ should be cut at $\gamma$.

According to the principle of planar microstrip Yagi-Uda antennas [3, 9], a reflector can be introduced in the endfire direction for backfire radiation enhancement. The reflector can be empirically shaped as an annular sector with open-circuited inner radius and short-circuited outer radius [19, 29–31], as shown in Figure 2(a). The coupling between the reflector and principal radiator can be electric or magnetic. Using the multiple-source model [25, 32], we can validate that electrical coupling may be beneficial for backfire radiation enhancement. In this case, a natural boundary condition of virtual perfect electric conductor (PEC) is introduced between them, such that the electric or $E$-field of the principal radiator can be coupled to the reflector in a capacitive manner with a retarded propagation phase. Propagating an odd-number time(s) of quarter-wavelength, an advanced phase would be attained owing to the inductive effect of shorting wall instead, so as the $E$-field could be reflected to yield enhanced radiation in the backfire direction. Thus, the width of the reflector should be set as $W_r = n\lambda/4$, and $n = 1, 3, 5...$

To predict the radiation behavior of the resultant antenna, six sources are symmetrically sampled on the peripheries of the principal radiator and reflector, respectively, as shown in Figure 2(b), where points 1 and 2 are the current antinodes with amplitudes of $A_{1,2} = 1.0$, and others are half-power ones with amplitudes of $A_{3,4,5,6} = 0.707$. Set Point 1 as the phase center of the whole antenna, thus the combined far field at arbitrary observation point $P$ can be calculated by the multiple-source model presented in [25, 33], and the combined far field can be represented by $F(\Theta, \Phi)$. It yields the configuration with detailed parameters as given in Figure 2(c).

2.2. Initial Parameters Estimation. As indicated in [25, 27], backfire radiation characteristic can be reasonable when $\alpha = 4\pi/3$ (240°) without exciting the first high-order radial $TM_{3\pi/\alpha,2}$ mode. A pair of shorting pins and slits are used to
Figure 2: Continued.
Figure 2: Continued.
disturb the fundamental TMₘₙ₁ mode and the odd high-order TM₅ₙ₁,₁ mode, respectively, so as to realize a triple-mode resonant, wideband-radiation characteristic [27]. The radiation modes within xy-plane under triple-mode resonance can be theoretically calculated by [28]. Thus, the initial value of the principal radiator can be determined as

\[ \alpha = 240.0^\circ, \quad R_0 = 26.6 \text{ mm}, \quad h_1 = 3.0 \text{ mm}, \quad \rho_1 = 22.0 \text{ mm}, \quad \beta = \pm 40.0^\circ, \quad L_s = 9.8 \text{ mm}, \quad W_r = 3.3 \text{ mm}, \quad \gamma = \pm 72^\circ \] [25, 27, 28].

For the reflector, the six-point source model [25, 33] is employed to determine \( \alpha_1 \) and \( R_1 \) [33]. According to our previous experience, the initial distance between the reflector and the principal radiator can be set to 0.075 \( \lambda \) [30]. Figures 2(d)–2(e) show the theoretical radiation pattern within xy-plane for different \( \alpha_1 \) and \( R_1 \). As can be seen from Figures 2(d)–2(e), when \( \alpha_1 = 80^\circ \) and \( R_1 = 65.0 \text{ mm} \), low side-lobe level can be simultaneously attained. The width \( W_r \) can be set as three quarter-wavelength, i.e., \( W_r = 40.8 \text{ mm} \). Thus, the initial parameters of the reflector can be set as \( \alpha_1 = 80^\circ, \quad R_1 = 65.0 \text{ mm}, \quad W_r = 40.8 \text{ mm}, \quad \text{and} \quad d_0 = 0.075 \lambda \). Therefore, the initial values of the critical parameters of the antenna have been estimated and approximately determined.

2.3. Parametric Studies. Based on the above theoretical results, the antenna is numerically simulated by using Ansys HFSS. A sufficiently large rectangular ground size [32] with \( L_g = 160.0 \text{ mm} \) and \( W_g = 130.0 \text{ mm} \) is used. The feed probe for better impedance matching is placed at \( (\rho_0, 0) = (22.5 \text{ mm}, 0) \) [27]. In the simulation, it is found that the impedance bandwidth, backfire gain, and first side-lobe level are all sensitive to the height of the reflector \( h_2 \). Accordingly, it also affects the width \( W_r \) and yields a modified \( W_r = W_r' + h_2 = n\lambda/4 \), and \( n = 1, 3, 5... \) As illustrated in Figures 3(a)–3(d), when \( W_r' = 33.0 \text{ mm} \) (\( n = 3 \), \( h_2 = 7 \text{ mm} \)) and \( \alpha_1 = 85^\circ \), better impedance matching, higher backfire gain, and lower first side-lobe level lower can be obtained.

Theoretically predicted and numerically simulated values are tabulated and compared in Table 1. As a result, a set of empirical design formulas with error of less than 17% of (1)–(7) can be attained for estimation in the initial step of design process [27]. Compared to the elementary antenna cases [26–28], the discrepancy of closed formulas is higher because of the interactions of the two radiators.
Figure 3: Continued.
have not been considered. Fortunately, they still exhibit acceptable engineering precision for estimation of most parameters.

\[
R_0 = \frac{X_{(9/4,1)}^{(0,1)}}{2\pi} \lambda_i
\]  

1

\[
J_{(3/4)}(k\rho_1) \approx J_{(9/4)}(k\rho_1),
\]

2

\[
\beta = \pm \frac{\alpha}{6} = 40^\circ,
\]

3

\[
\gamma = \pm \frac{3\alpha}{10} = 72^\circ,
\]

4

Figure 3: Parametric studies on the \( W'_r \) and \( \alpha_1 \). (a) \( W'_r \left( h_2 = 7.0 \text{ mm}, \alpha_1 = 85.0^\circ, \text{ and } R_1 = 65.0 \text{ mm} \right) \), (b) \( W'_r \left( h_2 = 7.0 \text{ mm}, \alpha_1 = 85.0^\circ, \text{ and } R_1 = 65.0 \text{ mm} \right) \), at 5.9 GHz, (c) \( \alpha_1 \left( h_2 = 7 \text{ mm}, W'_r = 33.0 \text{ mm}, \text{ and } R_1 = 65.0 \text{ mm} \right) \), and (d) \( \alpha_1 \left( h_2 = 7 \text{ mm}, W'_r = 33.0 \text{ mm}, \text{ and } R_1 = 65.0 \text{ mm} \right) \), at 5.9 GHz.
\[ L_s = \frac{\lambda_H}{4} + \frac{h_1}{2} \]  
\[ W_s = \frac{\lambda_H}{10}, \]  
\[ W_r = W_r' + h_2 = \frac{n\lambda}{4}, n = 1, 3, 5 \cdots, \]

where \( \chi_{9/4,1} \) is the first root of the first-order derivative of 9/4-order Bessel function of the first kind, \( k \) is the wave number, and \( \lambda_H \) is the wavelength corresponding to the TM_{15/4,1} mode's resonant frequency.

### 3. Measurement and Validation

According to Table 1, prototype antennas with \( W_r' = 33.0 \) mm (\( n = 3, h_2 = 7.0 \) mm) are fabricated and measured to validate the design approach. All antenna prototypes are measured by employing an Agilent's N5230A Vector Network Analyzer (VNA) and a Satimo’s StarLab near-field antenna measurement system.

Figure 4 illustrates the photograph of fabricated antenna. The measured and simulated reflection coefficients are shown in Figure 5, and it is observed that the fabricated antenna exhibits a wideband, triple-mode resonant characteristic from 4.0 GHz to 6.4 GHz (for \( |S_{11}| \leq -10 \) dB). Therefore, its measured impedance bandwidth is up to about 43.6%.

The simulated electric field distributions at 4.56, 5.02, and 5.84 GHz are shown in Figure 6 to illustrate the mode excitations. Similar to [27], it is clear that the high-order modes of the principal radiator and the reflector have been fully excited at 5.02 and 5.84 GHz. When the principal radiator is operating at TM_{9/4,1} and TM_{15/4,1} modes, the peripheral E-fields (\( E_z \)) of both radiator and reflector exhibit opposite directions. The principal radiator is electrically coupled to the reflector, which evidently proves the correctness of operation principle illustrated in Figure 2(a).

The simulated and measured normalized E-plane (zx-plane) and H-plane (xy-plane) radiation patterns at different frequencies are shown in Figure 7. The measured patterns well agree with the simulated ones. In xy-plane, the antenna exhibits a low first side-lobe level of less than -15.0 dB and a backfire radiation characteristic in V2X-band. Notably, the simulated cross-polarization level in the E-plane is lower than -40.0 dB and cannot be observed. In addition, it can be seen from the zx-plane that in V2X band, the antenna can provide low-elevation angles coverage ability from -60° to -90°, which may be beneficial for long-distance communications in these directions. Furthermore, the front-to-back ratio is greater than 15.1 dB in V2X-band within xy-plane, as shown in Figure 8.

As shown in Figure 9, the measured backfire gain varies less than 3 dB in the 5.0 to 6.0 GHz band. The maximum measured and simulated backfire gains in V2X-band are up to 7.3 dBi and 8.2 dBi, respectively. Both simulated and measured radiation efficiencies within the impedance bandwidth exceed 90%. These experimental results clearly
verify the correctness and effectiveness of the proposed design approach.

Finally, the proposed antenna is comprehensively compared with the classical Yagi-Uda antennas in Table 2 in terms of backfire/endfire gain, the first side-lobe level, front-to-back ratio, element number, and impedance bandwidth. Compared with [23, 25, 30, 34, 35], the advanced antenna exhibits higher backfire gain within xy-plane, which makes it more suitable for long-distance vehicular communications. Compared to the antennas in [14, 19, 21, 24, 25, 35], the first side-lobe level realized by the advanced approach is lower. Thus, it should...
Figure 7: Continued.
Figure 7: Continued.
potentially exhibit stronger anti-interference ability than the counterparts. Compared with the antennas in [14, 16, 19, 23, 25, 30, 34–36], the advanced antenna has a wider bandwidth so as to cover multiple spectra including the part of the 5G mobile communications in China, 5GHz-wireless local area network (WLAN) and V2X.

Figure 7: Simulated and measured radiation patterns at different frequencies. (a, b) xy- and zx-plane at 5.9 GHz, (c, d) xy- and zx-plane at 5.93 GHz, and (e, f) xy- and zx-plane at 6.0 GHz.
In addition, the presented antennas are fully implemented on air substrates, which is beneficial to reduce manufacturing costs compared to dielectric substrates [14, 16, 19, 21, 30, 35, 36]. Overall, the advanced approach can indeed yield higher backfire gain and lower side-lobe level simultaneously with fewer elements compared to most of the existing microstrip Yagi-Uda antennas. Therefore, the correctness, effectiveness, and generality of the advanced design approach have been comprehensively verified.
4. Conclusion

In this article, a design approach to triple-mode resonant patch antenna with low first side-lobe level and enhanced backfire gain for Vehicle-to-Everything (V2X) applications has been systematically proposed. Different from the traditional microstrip Yagi-Uda antennas, the electrical coupling property between the reflector and the principal radiator can be utilized to yield a broadband planar antenna with low side-lobe level and enhanced backfire gain. As a result, wide-band, triple-mode resonant planar antennas with simplified dual-element configuration, maximum backfire gain up to 7.3 dBi, and the first side-lobe level as low as -16.4 dB in the V2X-band have been successfully implemented. The advanced antenna design approach can be further applied in future high-performance vehicular antenna system developments.

Data Availability

We state that in our research article entitled "Backfire Patch Antenna with Enhanced Gain and Low Side-lobe Level under Triple-mode Resonance" submitted to International Journal of RF and Microwave Computer-Aided Engineering, no underlying data was collected or produced in this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was partly supported by the National Key Research and Development Program of China under grant no. 2021YFE0205900 and the National Natural Science Foundation of China under grant no. 61871233.

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