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Broadband Circularly Polarized Antenna with Stable Flat-Top Radiation Based on Metasurface

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Abstract

This paper presents a compact broadband circularly polarized antenna based on a metasurface. The antenna is designed to minimize transmission losses in microwave power transfer (MPT) systems while ensuring a stable flat-top radiation pattern for efficient energy transmission. The proposed structure is composed of aperture-coupled feeding and a metasurface in which four-unit cells are sequentially eliminated to enhance the antenna's circular polarization (CP) characteristic s. The antenna is fabricated and experimentally validated in this work, with measurements indicating strong agreement with the simulation results. Moreover, the antenna demonstrates excellent impedance matching across a wide bandwidth of 22.65% (4.46–5.85 GHz) and broadband CP characteristics with an axial ratio (AR) less than 3 dB over the 4.66–5.88 GHz range. The proposed antenna also maintains a stable flat-top (1-dB) radiation pattern throughout its operational frequency range. At 4.8 GHz, the flat-top beamwidths for the E-plane and H-plane are 58% and 60%, respectively, with a realized gain of 7.5 dBi. At 5.8 GHz, the flat-top beamwidths are higher than 56% in both planes, with a realized gain of 8.2 dBi. The proposed antenna offers superior performance in terms of compactness, a broadband flat-top beam, and broadband CP compared to those developed in previous studies.

Key Words: Broadband Antenna, Circular Polarization (CP), Compactness, Flat-Top Radiation Pattern (FTRP), Microwave Power Transfer (MPT).

I. Introduction

Wireless power transfer (WPT) has emerged as a pivotal technology, enabling the delivery of energy to mobile and Internet of Things (IoT) devices without the need for cables. Interactions between transmitters and receivers primarily influence WPT system performance. Conventional systems are affected by non-line-of-sight placement, resulting in energy loss and reduced efficiency, particularly in scenarios that demand mobility or flexibility. Several antenna methods have been recently proposed to improve power transmission efficiency, including high-gain antennas and circular polarization (CP) [1, 2]. Beamforming, which focuses energy into a narrow beam directed at the receiver [3], is a common method for enhancing the efficiency and range of WPT. While beamforming is highly effective at targeting single, stationary devices, it is limited in dynamic or multi-user environments in which devices may move or be spatially distributed. Flat-top radiation pattern (FTRP) antennas demonstrate unique advantages for overcoming these limitations [4, 5], as they radiate energy uniformly within the desired coverage area and prevent the efficiency drops typically caused by uneven radiation patterns. However, these designs have the drawback of narrow impedance bandwidth.

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WPT systems integrate functionalities such as communication and sensing, especially wireless information transmission. Simultaneous wireless information and power transfer (SWIPT) is a key feature in WPT systems, where the same emitted electromagnetic wave field is used for both energy and information transmission [6, 7]. Broadband antennas offer several advantages in these systems, making them crucial components for improving performance and versatility [8–10]. For instance, a previous work [8] details the use of a phased array antenna for far-field impulse radio ultrawideband WPT applications. Additionally, a wideband circularly polarized reflectarray antenna (RAA) has been introduced in the high-power microwave radiation field [9]. Simultaneous broadband impedance bandwidth and broadband FTRP–based metasurfaces have also been developed recently [11].

This study presents a broadband circularly polarized antenna with a stable FTRP to minimize losses in microwave power transmission (MPT) applications. The proposed design consists of a 4 × 4 patch array with corner cuts in which four sequential unit cells are removed to achieve the desired level of broadband FTRP performance. Simulation results demonstrate that the proposed antenna offers several advantages over competing antennas, including broadband impedance matching and CP while maintaining a FTRP over a wide frequency range.

II. Antenna Design and Performance

1. Antenna Geometry

Fig. 1 illustrates the overall geometry of the proposed FTRP antenna, which is composed of a metasurface with a 4 × 4 array of patches that serves as the antenna radiator. To achieve a wideband circular polarized characteristic, four sequential patches are selectively removed. The antenna is fed via a 50 Ω microstrip line. Moreover, CP performance is enhanced by the incorporation of two orthogonal slots in the ground plane. The proposed antenna uses two TLY-5 substrates (ε_r = 3, tanδ = 0.009) with thickness of h_1 and h_2. To realize the FTRP, the ground conductor plane is optimized to extend over a region approximately twice the size of a previous wavelength [4, 5]. The proposed antenna's parameter values are as follows: W_{s1} = 110, W_{s2} = 60, L_f = 59, W_f = 2.5, L_p = 24, g_1 = 0.2, g_2 = 0.5, C_1 = 30, C_2 = 4.5, θ_1 = 15°, θ_2 = 45°, h_1 = 0.8, h_2 = 3.1 (units: mm).

2. Design Evolution

The antenna was designed to achieve a FTRP characteristic that can be maintained over a wide frequency range. This design addresses several limitations of traditional wireless power transmission systems, including misalignment between the receiver and transmitter as well as angular losses. Utilizing aperture-coupled feeding and the radiated field of the radiator [4, 5, 14], has been shown to be an effective design method. In line with

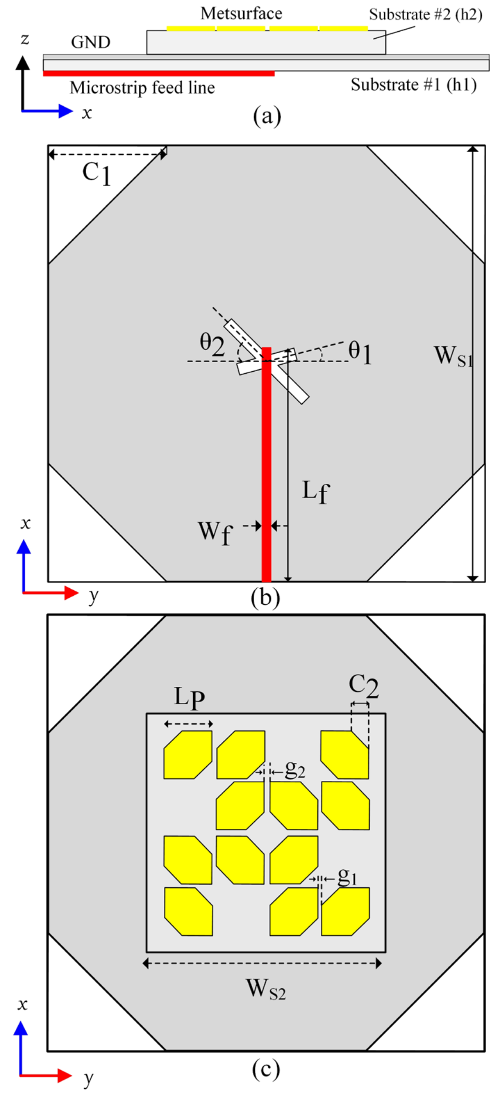

Fig. 1. Radiator geometry of the proposed antenna: (a) side view, (b) bottom view, and (c) top view.

the design method mentioned above, the FTRP is generated by carefully combined the aperture-coupled feeding and the radiator field of the metasurface, as expressed by [4]:

$$E_{total}(\theta,\phi) = E_{feed}(\theta,\phi) + E_{Meta}(\theta,\phi) \quad (1)$$

The E-field of the metasurface is represented by the array factor of the entire unit cells, which can be expressed as follows:

$$E_{Meta}(\theta,\phi) = E_{unit}(\theta,\phi).AF(\theta,\phi) \quad (2)$$

$$AF(\theta,\phi) = \sum_{m=0}^{3}\sum_{n=0}^{3} w_{mn} e^{jkd(m+n)(sin\theta cos\phi)} \quad (3)$$

where $E_{unit}(\theta,\phi)$ is the radiation pattern of a single unit cell, $AF(\theta,\phi)$ is the array factor, k is the wavenumber, d is the inter-element spacing, and w_{mn} denotes the excitation weight for each patch element. By physically removing patches (setting

$w_{mn} = 0$) and trimming the unit geometries, we control the metasurface's effective aperture and resulting beam shape. Given (1), the total field of the antenna structure is influenced by two key components: aperture-coupled feeding and a metasurface that functions as a radiator. The electric field of the feeding structure is primarily controlled by the size of the ground plane, which is optimized to approximately twice the wavelength at the operating frequency to achieve the FTRP characteristic. The metasurface is positioned above the aperture-coupled feeding to enhance the FTRP and support broadband CP.

The antenna's detailed design steps are illustrated in Fig. 2 to validate the broadband FTRP characteristic. To demonstrate the effect of the metasurface on the radiated field, the aperture-coupled feeding at the bottom remains unchanged and features two orthogonal slots. In the first step, a 4 × 4 square patch array is placed on the top layer of the structure. In the second step, four sequential patches are removed to control the electric field, enhancing the FTRP. For the third design iteration, two additional corners are cut from each patch, improving current control and further refining the antenna's radiation characteristics. Finally, in the fourth design, four sequential patches are removed from the third structure, resulting in the proposed design.

Fig. 3 presents the simulation results for the four designs, including the reflection coefficient, axial ratio (AR), and realized gain. The initial design (antenna #1) exhibits multiple resonance frequencies and axial ratios. In the second design, the impedance bandwidth improves at lower frequencies, and a wider beamwidth is achieved. The third design, which incorporates cut corners, demonstrates improved impedance matching and yields an AR closer to broadband CP. The final design integrates all these enhancements, achieving broadband CP and a FTRP across the entire frequency range.

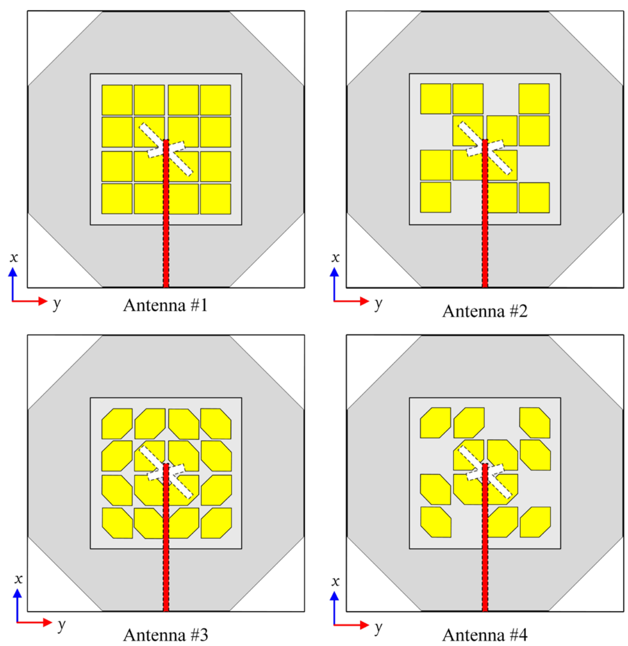

Fig. 2. Evolution of the proposed antenna with four-antenna geometry.

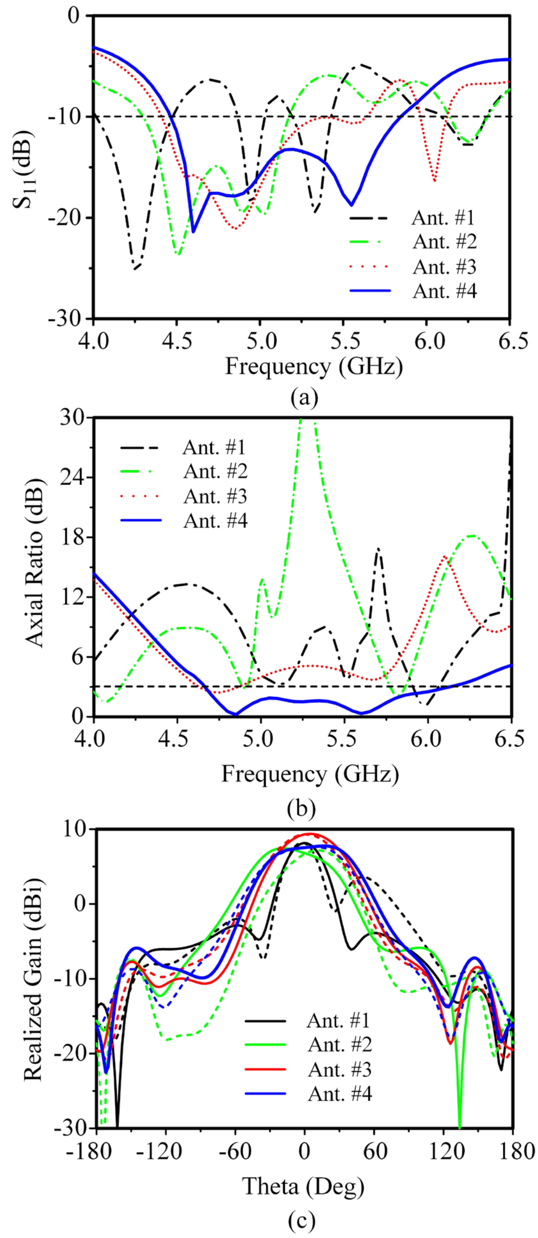

Fig. 3. Performances of the antenna evolution: (a) reflection coefficients, (b) axial ratio, and (c) realized gain (line, E-plane; dotted line, H-plane).

A parametric study was conducted on unit cell size (L_p) and the inter-cell gap (g_2) to further verify the impact of the metasurface on the overall radiation performance of the antenna, as shown in Fig. 4. The results indicate that increasing L_p leads to notable improvements in gain, confirming that unit cell size directly influences radiation enhancement. Furthermore, as g_2 increases, the AR bandwidth remains below 3 dB, and an AR shift toward lower values is observed in the higher band. These findings confirm that both the AR bandwidth and the FTRP can be tuned by optimizing the metasurface parameters in accordance with the formulation presented in (2). In addition, to further illustrate the CP mechanism, the surface current distribution on the metasurface is simulated at three resonant frequencies, as shown in Fig. 5. The current on the metasurface rotates by 90° after a quarter of the time period at 4.8 GHz, 5.2 GHz, and 5.8 GHz.

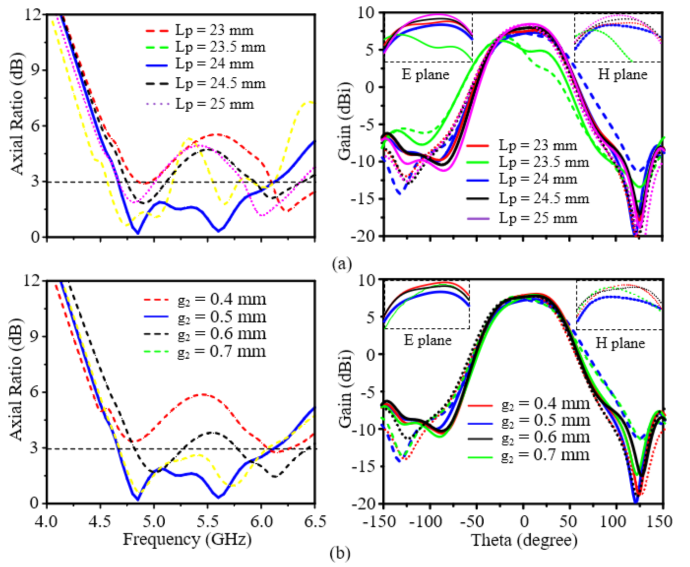

Fig. 4. Parameter study for broadband CP antenna with influence of: (a) L_p and (b) g_2.

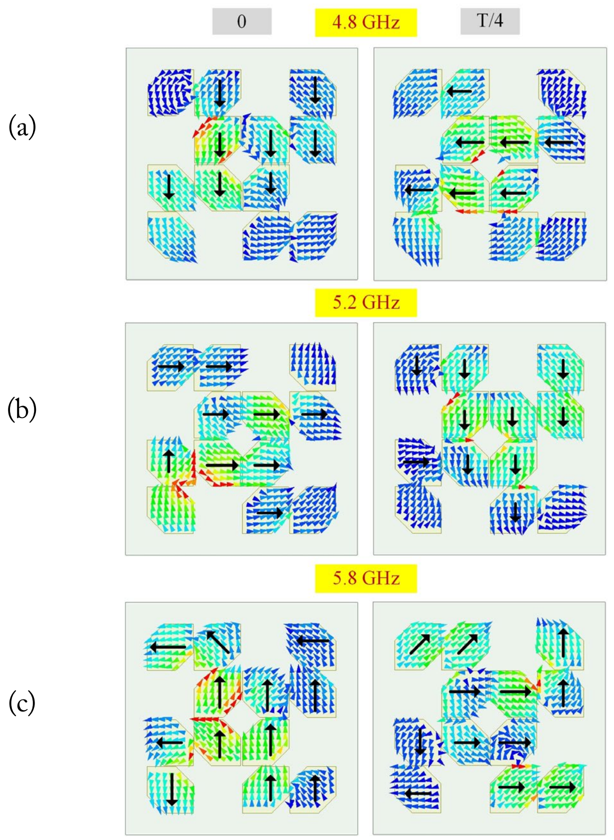

Fig. 5. Current distribution on the metasurface of the proposed geometry at 4.8 GHz (a), 5.2GHz (b), and 5.8 GHz (c).

III. MEASUREMENT RESULTS

To validate broadband CP antenna performance, the proposed antenna was fabricated with overall dimensions of 110 mm × 110 mm × 3.9 mm, as depicted in Fig. 6. To ensure the antenna's structural stability and reduce measurement tolerance, the two substrate layers were stacked and mechanically bonded using four plastic screws. Fig. 7(a) illustrates the reflection coefficient, indicating a good impedance matching of 22.65% (4.46–5.85 GHz). Furthermore, in the range of overlap bandwidth, a 3-dB axial ratio is obtained from 4.66 GHz to 5.88 GHz, where the peak gain is achieved at 8.2 dBi at 5.8 GHz, as presented in Fig. 7(b).

To determine whether the antenna maintains FTRP within the operation frequency range, the 2D normalized gain is presented at 4.8 GHz, 5.2 GHz, and 5.8 GHz, as shown in Fig. 8. The results indicate that the 1-dB beamwidths at 4.8 GHz were obtained at 58° and 60° in the E-plane and H-plane, respectively.

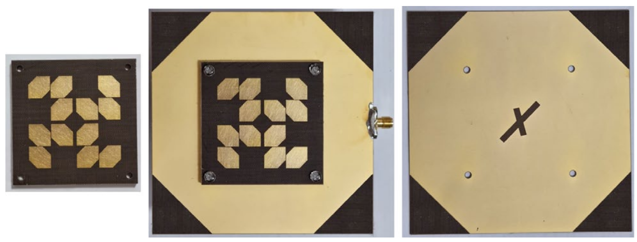

Fig. 6. Fabrication of the proposed antenna.

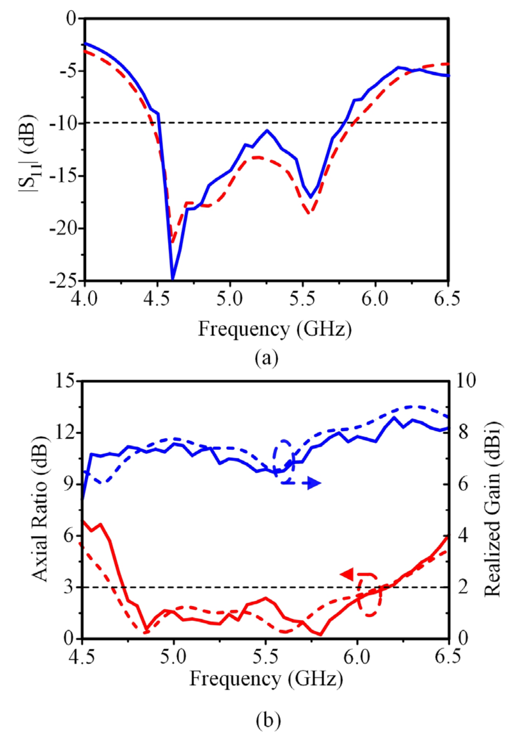

Fig. 7. (a) Reflection coefficient and (b) axial ratio and realized gain (line, measurements; dotted line, simulation).

At 5.2 GHz, the 1-dB beamwidths are 55° and 53° for the E-plane and H-plane, respectively. Finally, 1-dB beamwidths at 5.8 GHz account for higher than 46° in both planes. In addition, the proposed antenna has high left-hand circular polarization (LHCP) gain and low right-hand circular polarization (RHCP) gain.

Table 1 describes the comparison between the proposed antenna and the recently established FTRP [11–14]. The proposed antenna obtains high gain and is compact in size. Furthermore, the structure not only achieves broadband FTRP but also possesses CP characteristics within the impedance bandwidth. In summary, the proposed structure demonstrates the ability to radiate uniform power over a wide frequency range, effectively minimizing losses and tolerances in MPT applications.

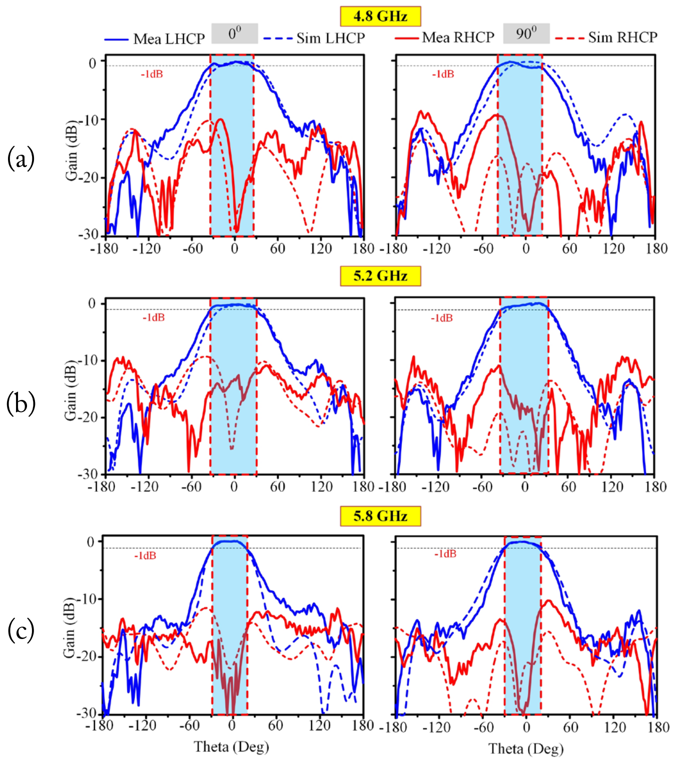

Fig. 8. Flat-top radiation patterns at 4.8 GHz (a), 5.2 GHz (b), and 5.8 GHz (c).

IV. Conclusion

This paper proposes a broadband CP antenna with a stable FTRP for use in wireless power transmission applications. Broadband CP is achieved by combining a metasurface with a coupled antenna in which four sequential patches are removed. The simulation results show that the antenna provides an impedance bandwidth of 22.65% (4.46–5.85 GHz) with a return loss lower than −10 dB. In addition, a 3-dB AR was achieved from 4.66 GHz to 5.88 GHz. Notably, a stable FTRP is maintained throughout the operational frequency range within the overlap between the impedance bandwidth and AR. The proposed antenna offers advantages such as high gain, compactness, broadband CP, and stable FTRP gain, making it highly suitable for dynamic MPT environments such as UAVs, IoT, and SWIPT applications.

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Table 1. Comparison of the proposed flat-top antenna and those in the most recent relevant works

Study	Method	Flat-top bandwidth (%)	Polarization	Peak gain (dBi)	Electrical size (λ_0^3)
Ran et al. [12]	Fabry-Pérot cavity	20.5	LP	11	2.37×2.37×0.67
Ren et al. [13]	Dielectric lens	40	LP	12.4	2.2×2.5×3.4
Geng et al. [14]	SIW	28.57	LP	8.8	10×1.5
Li et al. [11]	Meta, patch	40	LP	8.4	1.96×1.96×0.09
Proposed	Meta, patch	22.65	CP	8.2	1.91×1.91×0.066

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