The Influence of the Geometry of Antenna Elements with Elliptical Polarization on Their Characteristics

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***Abstract*—This paper presents electrodynamic simulation of six patch antenna configurations: a patch with a rectangular slot, an H-shaped patch, a patch with an asymmetrical protrusion, a patch with a 90° corner cutout, a diamond-shaped patch with chamfered corners, and a patch with a central rectangular slot located at 45°. Diagonal and axial feeding methods of the antenna element (AE) were used. It was found that modifications of the patch antenna configuration led to changes in the parameters of characteristic modes, thereby providing a different number of resonances on the reflection coefficient (S_{11}) of the antennas. For 6 configurations, the following were calculated: S_{11}, axial ratio (AR), gain and the radiation patterns (RP). The best AR was 17.4 dB for configuration 2 with diagonal excitation, while configuration 6 with axial excitation showed the best matching of –20.26 dB and AR = 18 dB. All the configurations demonstrated high gain, ranging from 6.86 to 7.14 dB. A 45° angle deviation led to a decrease in gain, amounting to 3–3.12 dB, with diagonal excitation of the AE. With axial excitation of the AE, the gain was 2.5–3.22 dB for three configurations. The electrodynamic simulations confirmed the potential of configuration 2 and 6 for further optimization of the array element junction position to achieve AR close to unity. The aim of the work is to evaluate the influence of the elliptically polarized AE geometry on the electrical characteristics.**

Keywords—Elliptical polarization, gain, antenna elements, patch antenna, axial ratio, planar antenna, feed point.

I. Introduction

In the modern telecommunications industry, a critical parameter that ensures the reliability and noise immunity of communication channels is the use of antennas with circular polarization (CP) [1], [2], [3], [4]. CP minimizes losses associated with multipath signal propagation and the mutual orientation of transmitting and receiving devices. A key quality indicator for such an antenna is the axial ratio (AR) [5], [6], which should approach unity within the specified operating frequency band. Achieving CP requires the excitation of two orthogonal mode components with equal amplitudes and a 90° phase shift. In the case of ideal symmetry, these modes resonate at the same frequency. However, any asymmetry introduced into the structure causes the mode frequencies to diverge. This is the primary reason for poor AR in the operating band. Effective management of the modal structure allows not only shifting the resonance towards the target frequency but also ensuring AR stability over a wider spectrum. Traditional methods for achieving CP, which are based on simple modifications of rectangular patches, often exhibit a narrow operating band [7]. To overcome these limitations, the focus has shifted towards studying modified geometries, such as incorporating slots, notches, or stepped contours [8], [9], [10]. These modifications allow for controlling the modal structure and widening the operating band. However, the systematic influence of specific geometric modifications and non-standard feed point locations on the modal structure has not been studied sufficiently. The multiple resonances observed in the simulated structures demonstrate the complexity of simultaneously managing two orthogonal modes. The relevance of this work is driven by necessity to develop compact and highly efficient antenna systems operating in frequency ranges critical for modern wireless data transmission. Consequently, the objective of this research is to evaluate the influence of the geometry of elliptical polarization antenna elements on their electrical characteristics. To achieve this objective, this study presents a comparative analysis of six different antenna element (AE) configurations, which vary in both the geometry of their outline and their excitation methods.

The key contribution of this work lies in the detailed investigation of how these structural variations in the AE specifically impact the overall electrical characteristics of elliptical polarization.

II. Materials, Design and Simulation Approaches

A. Simulation Parametrs

The simulation was performed in the CST Studio Suite electromagnetic simulation environment using a frequency domain solver. To ensure the accuracy of the results, we applied adaptive mesh refinement limited to 8 passes. The stopping criterion for the process was an accuracy of 0.02 for the magnitudes of the S-parameters at all ports. The calculations were carried out in the frequency range of 1–4 GHz with 10 frequency samples. The boundaries of the computational domain were simulation as open space. The distance from the boundaries of the configuration under investigation to the outer boundary of the computational domain along all axes was a quarter of the wavelength.

The preliminary dimensions of the AE were determined as shown in Fig. 1. As the substrate material, we used AD255C with certified parameters of relative permittivity $\varepsilon_r = 2.55$ and dielectric loss tangent $\tan\Delta = 0.0014$. The geometric dimensions of the patch were as follows (mm): patch

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diameter $d = \lambda/2 = 42.11$, patch thickness $t = 0.035$, length (L) and width (W) were equal to the wavelength and amounted to 84.22. The patch was designed for a frequency of 2.4 GHz and made of copper with a thickness of $t = 0.035$ mm. The wavelength was calculated using formula (1):

$$\lambda = \frac{c}{f * \sqrt{\varepsilon_r}} \tag{1}$$

To analyze the characteristics of the configurations, we used two different approaches to feed point placement: diagonal (Fig. 1) and axial (Fig. 2) [8]. The feed point parameters were calculated as the parameters of a coaxial transmission line. The configuration of the AE layers is presented in Fig. 3. The AE feed point was implemented using a via; the via diameter d = 1 mm and the outer diameter of the coaxial line D = 3.5 mm were calculated using formula (2):

$$Z_0 = 60 \ln\left(\frac{D}{d}\right)\sqrt{\frac{\mu}{\varepsilon}} \tag{2}$$

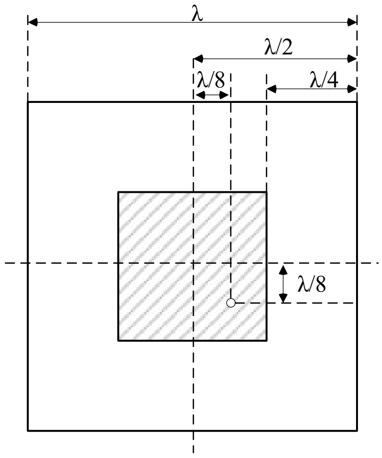


Fig. 1. Schematic diagram of the AE dimensions with diagonal feed point placement.

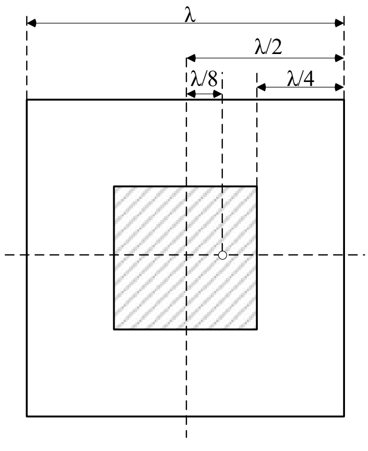


Fig. 2. Schematic diagram of the AE dimensions with axial feed point placement.

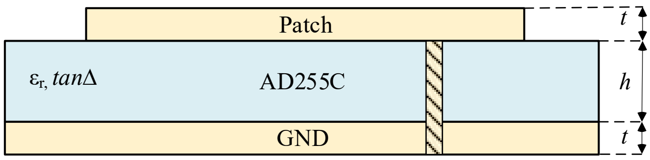


Fig. 3. Layer stack of a patch antennas.

B. Antenna Element Configurations Under Study

This study presents six configurations of antenna elements (Table I). The analysis involved various modifications of the AE configurations: slots, protrusions, chamfered corners, and notches. The electrical geometry of an antenna element directly dictates the distribution of currents and voltages on its surface. This distribution, in turn, shapes the radiated electromagnetic field characteristics, including its polarization. Changes in shape, size, feed point location, and the presence of discontinuities can alter the symmetry of the current distribution. A symmetric current distribution typically leads to more predictable and often linear polarization. Disrupting this symmetry, achieved through geometric modifications, is the key mechanism for generating elliptical or circular polarization. For instance, offsetting the feed point or introducing asymmetrical features allows for the creation of orthogonal field components that, with specific amplitude and phase relationships, form elliptical or circular polarization.

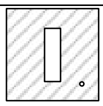
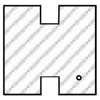
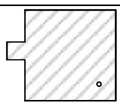
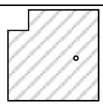
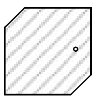
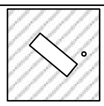
Patch antennas are one of the most prevalent types of antennas in modern electronic systems due to their advantages, such as ease of manufacturing, compactness, low profile, and the ability to integrate with other components on a printed circuit board. However, basic patch antenna configurations often radiate linearly polarized fields. To achieve more complex polarization characteristics, such as elliptical or circular polarization, the application of specialized design techniques is necessary.

Among the most common and effective methods for modifying patch antennas to control their polarization characteristics, which we investigate, are: introducing slots and cutouts, such as rectangular or H-shaped, which disrupts the symmetry of the current distribution; altering element shape and creating asymmetry by adding protrusions or using asymmetric element geometry, which is a key mechanism for disrupting the symmetry of current distribution; corner treatment, such as chamfering or cutting, which affects boundary conditions and local current distribution, contributing to more uniform polarization propagation; and varying the feed point location, especially diagonal displacement, which is a powerful tool for exciting two orthogonal modes with the necessary amplitude and phase relationships. These geometric features act as artificial discontinuities that locally alter the electrical dimensions and surface currents, thereby shaping the desired electromagnetic field distribution. The asymmetry introduced by such modifications directly contributes to the generation of elliptical polarization. The six antenna element configurations presented in this work were chosen for a systematic investigation into the influence of combinations of these standard and effective design techniques on polarization characteristics.

The first three AEs utilized a diagonal feed point location. Configuration 1 is a patch with a central rectangular slot and a feed point shifted diagonally from the center. Configuration 2 is a patch with a symmetrical H-shaped form with cutouts, diagonally fed. Configuration 3 features a patch with an asymmetrical step, with similar diagonal excitation.

The second group of AEs had an axial feed point. Configuration 4 demonstrates a patch with a 90° corner cut. Configuration 5 is a square patch with chamfered corners. Configuration 6 is a patch with a central rectangular slot positioned diagonally relative to the center.

TABLE I. ANTENNA ELEMENT CONFIGURATIONS

Configuration	Patch View	Feed Point
1		Diagonal Feed
2		
3		
4		Axial Feed
5		
6		

III. SIMULATION

A. Configurations with Diagonal Feed Point

The results of the electrodynamic simulation for configuration 1, 2, and 3 are shown in Fig. 4. Configuration 1 exhibited three resonant responses detected at 1.9, 2.35, and 3.3 GHz.

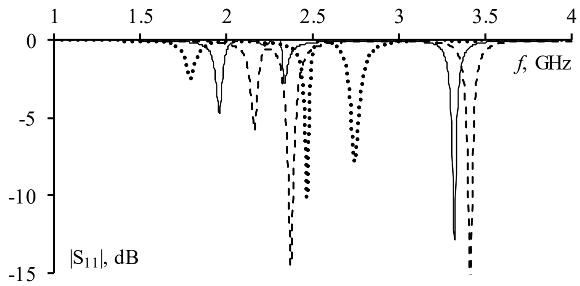
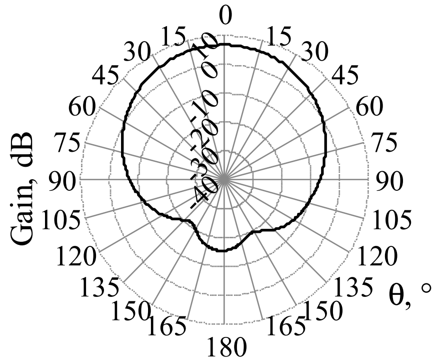
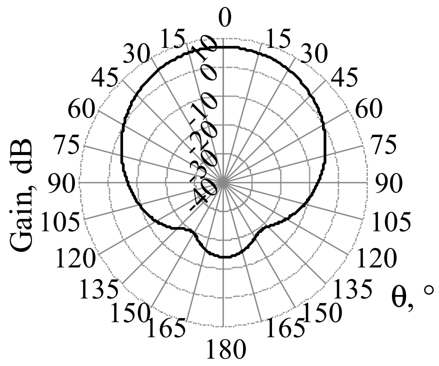


Fig. 4. Frequency dependence of $|S_{11}|$ for AEs: configuration 1 (—), 2 (…), and 3 (- - -).

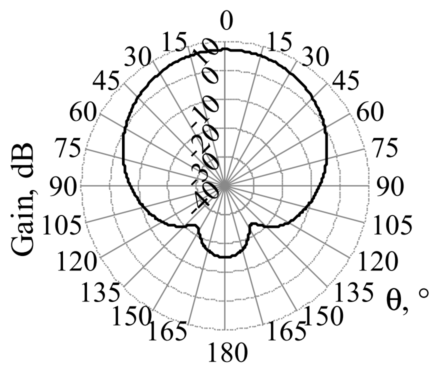
The inherent geometric asymmetry in the AE configuration generated characteristic modes with varying parameters, consequently influencing the count of S_{11} resonances. The deepest reflection notch in this setup, –13 dB, occurred precisely at 3.3 GHz. Shifting to configuration 2, three resonant points were still present, although shifted to 1.8, 2.4, and 2.7 GHz. The highest magnitude of reflection achieved here was –11 dB, with this peak occurring centrally at 2.4 GHz. Finally, configuration 3 presented its own set of three resonances, positioned at 2.15, 2.4, and 3.4 GHz. This configuration yielded the strongest performance overall, registering a maximum reflection coefficient of –19 dB, which was strongly correlated with the highest frequency point at 3.4 GHz. Fig. 5 shows the polar diagram for these three configurations.



a



b



c

Fig. 5. Radiation patterns of AEs: no.1 (*a*), no.2 (*b*), and no.3 (*c*).

Since the gain values for the 45° angles were identical due to the symmetry of the configuration, the results are presented for only one of the directions. The maximum gains for configuration 1 and 2 were 6.91 and 6.86 dB, respectively. At a 45° angle deviation, the gain was 3 dB for both configurations. For configuration 3, the results were practically the same; the maximum gain was 6.97 dB, and at a 45° angle deviation, the gain was 3.12 dB. The results are summarized in Table II. As can be seen from Table II, the minimum AR was achieved with configuration 2.

TABLE II. SIMULATION RESULTS OF AE RADIATION PATTERNS

Configuration	AR	Gain
1	34.42	6.91
2	17.4	6.86
3	37.44	6.97

B. Configurations with Axial Feed Point

The results of the electrodynamic simulation for configuration 4, 5 and 6 are shown in Fig. 6. For configuration 4, two distinct resonances were observed at frequencies of 2.3 and 2.5 GHz.

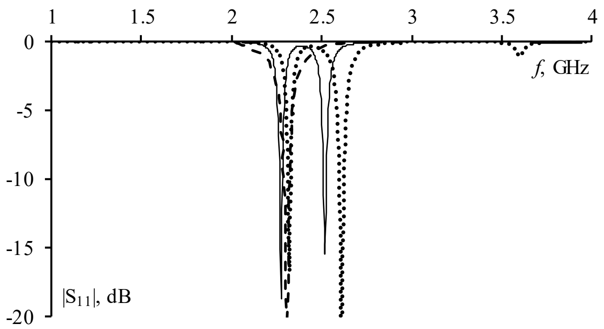


Fig. 6. Frequency dependence of $|S_{11}|$ for AEs: configuration 4 (—), 5 (…), and 6 (- - -).

The maximum reflection coefficient was achieved at a frequency of 2.3 GHz and amounted to –18.7 dB. For configuration 5, three resonances were observed at frequencies of 2.35, 2.6, and 3.5 GHz. The maximum reflection coefficient was achieved at a frequency of 2.6 GHz and amounted to –20 dB. For the last configuration, one distinct resonance was observed at a frequency of 2.3 GHz. The reflection coefficient was –20.26 dB. Fig. 7 shows the polar diagram for the three configurations. The obtained results are summarized in Table III and demonstrate that the minimum AR is achieved with configuration 6.

TABLE III. SIMULATION RESULTS OF AE RADIATION PATTERNS

Configuration	AR	Gain
4	22.98	7.14
5	26.29	6.97
6	18	7

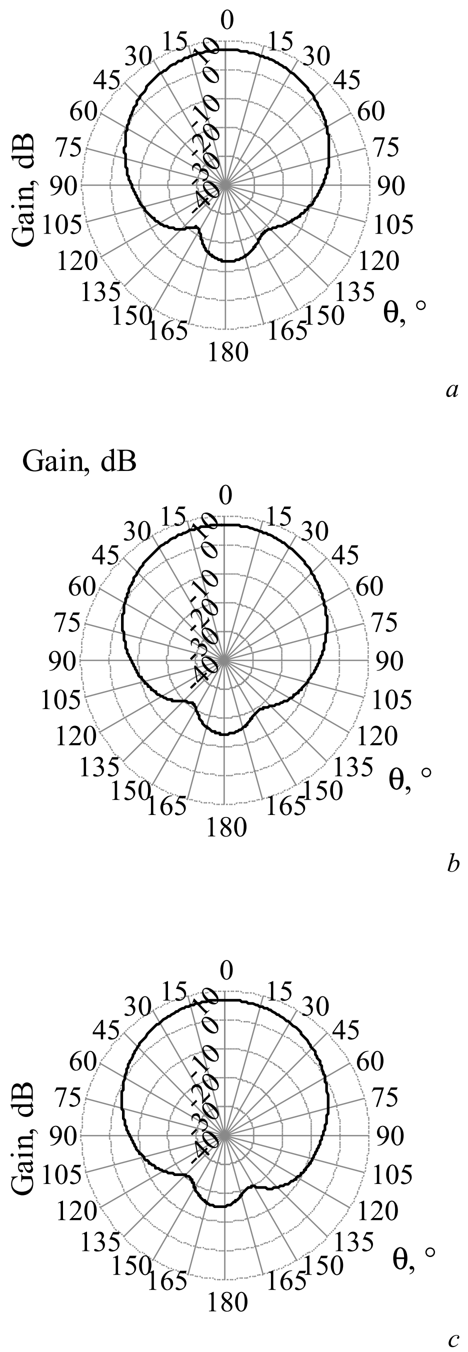


Fig. 7. Radiation patterns of AEs: no.4 (*a*), no.5 (*b*), and no.6 (*c*).

The maximum gains for configuration 4, 5, and 6 were 7.14, 6.97, and 7 dB, respectively. For configuration 4, with a 45° angle deviation, a decrease in gain to 2.5 dB was recorded. In the case of configuration 5, the same deviation led to a reduction in gain to 2.93 dB. For configuration 6, the gain was 3.22 dB.

IV. ANALYSIS OF RESULTS

The results showed that with a diagonal feed point location, three distinct resonance peaks were observed for all three configurations. The best matching, reaching –19 dB at a frequency of 3.4 GHz, was recorded for configuration 3. However, the lowest axial ratio, equal to 17.4 dB, was achieved with configuration 2. The configurations with an axial feed point demonstrated fewer resonances in the considered frequency range. configuration 6 showed the highest reflection coefficient at a frequency of 2.3 GHz, which amounted to –20.26 dB, and at the same time provided the best axial ratio equal to 18. The gain for all six configurations remained at a high level, from 6.86 to 7.14 dB. Overall, configuration 2 and 6 achieved the lowest axial ratio values, 17.4 and 18 dB, respectively.

V. CONCLUSION

In this work, we carried out electrodynamic simulation of six configurations of planar AEs with elliptical polarization. We investigated the influence of two main approaches to feed point placement: diagonal and axial. It was found that modifications to the patch antenna configuration alter the parameters of the characteristic modes, thereby causing a varying number of S_{11} resonances depending on the frequency. Importantly, the polarization's direction of rotation remained constant regardless of the excitation method used. The calculated S_{11}, AR, gain, and radiation patterns confirmed the significant potential of configurations 2 and 5 for further optimization toward achieving an AR value close to unity.

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