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Performance Evaluation of a Two-Arm Four-Turn Archimedean Spiral Antenna

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ABSTRACT

In this study, a two-arm, four-turn copper Archimedean Spiral Antenna (ASA) was designed to work in the frequency range of 0.747 to 29.858 GHz. The antenna has an inner and outer radius of 1.5989 mm and 63.956 mm, respectively, and a thickness of 0.03556 mm. The goal is to create a source that can provide a nearly omnidirectional, hemispherical 3D radiation pattern on both antenna sides in the elevation planes that is appropriate for mobile and related applications. The simulation yields a broadband, bidirectional radiator with a dumbbell radiation pattern that has a peak gain of 5.48 dB at the two opposite boresights, which decreases to -5.75 dB in directions parallel to the antenna elevation planes. Approximately 7.53% of the boresight gain is available in these parallel elevation planes. Future work will consider an array of ASAs to create a source that radiates a near omnidirectional hemispherical 3D radiation pattern on both antenna sides in the elevation planes.

Keywords: Omnidirectional Radiation, Dumbbell Radiation, Self-complementary, Frequency-independent

RESEARCH HIGHLIGHTS

- Designs and evaluates a broadband two-arm, four-turn Archimedean spiral antenna.
- Simulation shows bidirectional radiation with a peak gain of 5.48 dB across 0.747‑29.858 GHz.
- The antenna is relevant for mobile communication, sensing and direction-finding applications.

HOW TO CITE

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1. Introduction

The evolution of wireless communication systems has necessitated the development of antennas that provide wide bandwidth, compact size, and consistent radiation patterns. The ASA stands out among various designs due to its frequency-independent characteristics and circular polarization capabilities. Its geometry makes it frequency-independent, enabling operation across a wide frequency range without significant performance changes, which makes it ideal for broadband applications (Chun *et al.*, 2020). This wideband capability is particularly advantageous for communication systems that require consistent performance across multiple frequency bands. The spiral geometry naturally supports circular polarization, allowing the antenna to receive signals regardless of their polarization orientations effectively. This feature minimizes signal degradation due to polarization mismatch and is crucial for satellite communications, surveillance, electronic warfare, and radar applications (Kumar *et al.*, 2018). These features, frequency-independent and polarization-flexible, render the antenna especially suitable for applications that demand broadband performance and uniform radiation, such as mobile communication, sensing systems, and related applications (Xiao *et al.*, 2024).

The ASA operates on the principle of self-complementarity, which allows it to maintain consistent input impedance and radiation patterns over a wide frequency range. Self-complementary implies that the conductive arms and the spaces between them have the same shape and dimensions when viewed as a planar pattern (Liu *et al.*, 2008). This design provides frequency-independent input impedance, typically around 188.5 ohms, which makes matching easier across a wide bandwidth (Chen and Huff, 2014). The stable impedance ensures that signal loss from the source to the antenna is minimized, allowing the antenna to efficiently radiate in a consistent beam shape. A simple extension of the spiral arms, while preserving self-complementarity, can lower the operating frequency without increasing physical dimensions (Ahn *et al.*, 2015).

ASAs are bidirectional, emitting electromagnetic waves in two opposite directions, typically both forward and backward relative to the antenna's plane. This naturally arises from the antenna's planar, symmetrical structure and the absence of a reflective backing. This design allows energy to radiate equally from both faces of the spiral, resulting in a pattern resembling two lobes projecting in opposite directions (Rajalakshmi *et al.*, 2023). Bidirectional spiral antennas are highly useful in applications that require simultaneous transmission or reception from both sides of a platform, such as sensing systems, environmental monitoring, and communication setups. This configuration can effectively cover two spatial regions with a single antenna, potentially reducing system complexity and hardware costs. The study aims to develop an ASA capable of delivering a virtually omnidirectional, hemispherical 3D radiation pattern in both antenna elevation planes.

Prior Research on Comparable ASA

Mohamad *et al.* (2015) designed a two-arm, four-turn ASA with 1.65 mm conductor width and spacing, for a nominal impedance of 188 Ω, and fed with equal-amplitude, anti-phase signals. It operates between 3–10 GHz, with inner and outer diameters of 4 and 60 mm, respectively. The study converted the bidirectional ASA to unidirectional by backing the one plane of the antenna with a frequency-selective surface reflector. The reflector consists of a dual-layer periodic array of conductive rings tuned to transmit at 3–6 GHz and reflect at 7–10 GHz, with insertion loss less than 0.25 dB in the reflection band. Both simulation and measurements show significant improvement over the unbacked spiral. In the 3–6 GHz range, the antenna exhibits an enhanced front-to-back ratio of less than 10 dB, reaching a maximum of about 25 dB. In the 7–10 GHz band, gain increases by about 3 dBi, and the originally bidirectional pattern becomes effectively unidirectional, while preserving wideband circular polarization.

Simulation

This antenna was simulated with a copper thickness of 0.03556 mm in MATLAB to produce a center-fed ASA, and the associated 3D, elevation, and azimuth radiation patterns, respectively. The range of frequency of the antenna were estimated using its inner and outer radii of 1.5989 mm and 63.956 mm. According to Sharma and Bernhard (2020) and Adenodi (2023), the upper and lower frequencies are estimated as:

$$f_u = \frac{c}{2\pi r_{in}} = \frac{3 \times 10^8}{2 \times 3.142 \times 1.5989 \times 10^{-3}} = 29.858\ GHz$$

$$f_l = \frac{c}{2\pi r_{ou}} = \frac{3 \times 10^8}{2 \times 3.142 \times 63.956 \times 10^{-3}} = 0.747\ GHz$$

The spiral growth rate is

$$g = \frac{r_{ou} - r_{in}}{2\pi n} = 2.48 \times 10^{-3}$$

A small growth rate ensures a tighter spiral, more turns, and wider bandwidth while favoring beamwidth, directionality, and polarization purity.

2. Results and Discussion

The simulated two-turn four-arm ASA presented in Figure 1 has a dimensions is about 11 cm square because of the small growth rate. The feed point at the center distributes signals with 90° phase shifts between the arms to generate right-hand and left-hand circular polarizations in opposite directions. This dual-polarization capabilities is an improvement on radiation symmetry that is impossible with two-arm antenna. Mohamad *et al.* (2015) designed a similar antenna but backed by a frequency selective surface reflector. The antenna in the current study is a balanced, planar spiral suitable for wideband, dual-polarized and bidirectional operations without backing. Such antenna typically found applications in Radar system, directional finding broadband communications, surveillance, FRID and IoT.

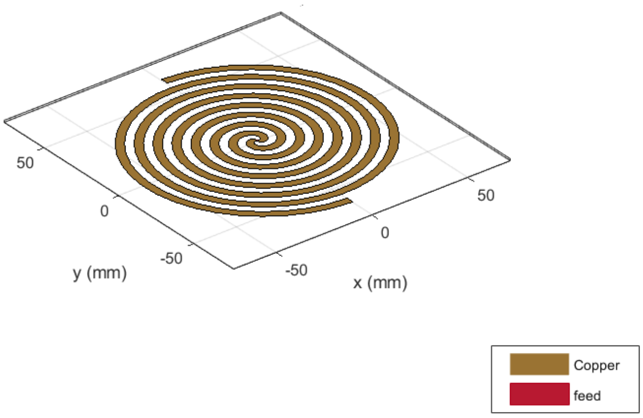

Figure 1: *A Two-Arm Four-Turn Archimedean Spiral Antenna*

Figure 2 shows the 3D radiation pattern of the simulated ASA, with a maximum gain of 5.48 dBi and a minimum gain of -5.75 dB. The pattern reveals the characteristic feature of unbacked ASA, a bidirectional radiation with two prominent lobes radiating away from both planar surfaces of the antenna. This implies the antenna emits energy equally in both forward and backward directions, corresponding to right-hand circular polarization and left-hand circular polarization, respectively. The near-perfect symmetry indicates minimal distortion, making this antenna ideal for applications requiring dual-polarized or omnidirectional hemispherical coverage, such as direction finding, electromagnetic compatibility testing, or wideband communication systems. The 3D pattern shows broad elevation coverage with uniform gain around the z-axis but the gain drops significantly around the lobe equatorial plane. In contrast, the FSS-backed design transforms the inherently bidirectional ASA into a unidirectional radiator, reflecting backward radiation in-phase reinforcing the forward wave in the 7–10 GHz range (Mohamad *et al.*, 2015).

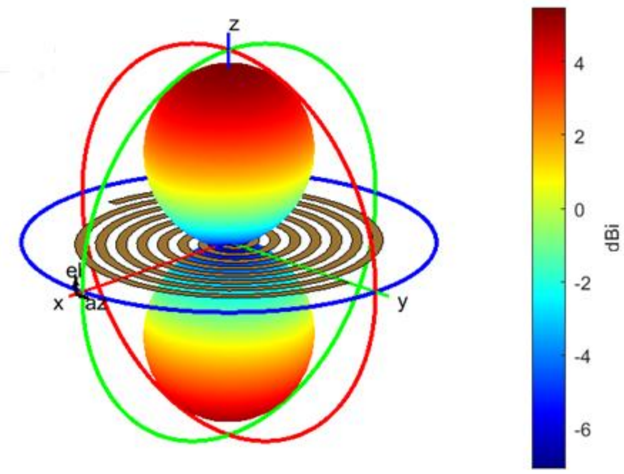

Figure 2: *Bidirectional Radiation Pattern*

The elevation radiation pattern of the ASA, as depicted in Figure 3, reveals a distinctive bi-directional figure-eight pattern. This pattern demonstrates strong lobes centered around the 90° and 270° elevation angles, indicating that the antenna radiates efficiently perpendicular to its plane. The peak gain of 5.48 dBi highlights a moderate radiation intensity in those directions. This makes the antenna highly suitable for applications where signals need to propagate sideways from the antenna's orientation, such as in airborne or mounted systems with vertical clearance on both sides. The symmetrical figure-eight shape in the elevation plane also indicates that the antenna provides predictable and balanced vertical radiation, ensuring consistent signal strength in both main directions. The nulls at 0° and 180° elevation angles exhibit very low radiation along the axis perpendicular to the antenna’s plane. This behavior can be a drawback in situations where coverage directly above or below the antenna is necessary. However, it is ideal for ground surveillance or horizontal communication applications, where vertical beam steering is not required, such as mobile networks. This antenna supports circular polarization, which contributes to signal robustness in multipath environments and improves performance when the antenna's orientation varies. This, combined with the stable elevation gain across a wide frequency range, underscores the antenna's wideband performance, making it suitable for frequency-agile systems such as spectrum monitoring, direction finding, and electromagnetic compatibility measurements. In contrast, the elevation patterns in the 7–10 GHz band of the FSS backed ASA transform from bidirectional to unidirectional beams, with strong forward lobes while suppressed back lobes, resulting in front-to-back ratios exceeding 10 dB (Mohamad *et al.*, 2015).

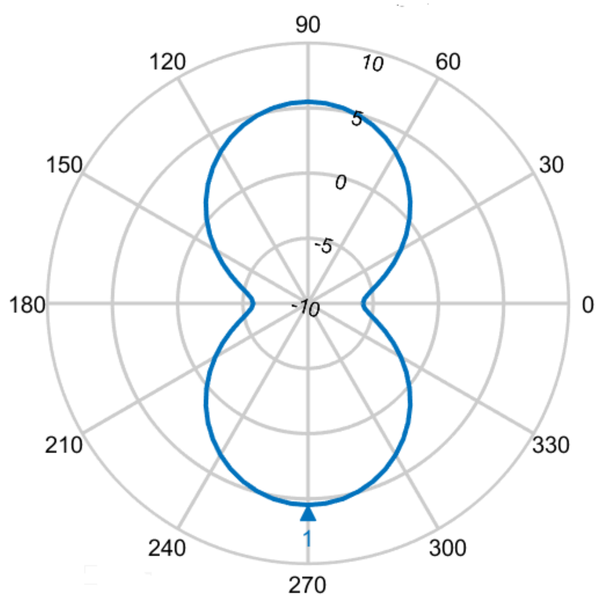

Figure 3: *Elevation radiation Pattern*

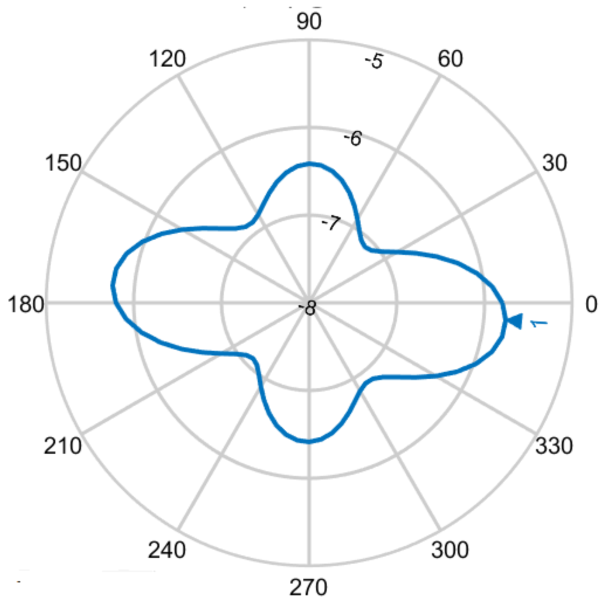

Figure 4: **Azimuth Radiation Pattern**

The azimuth radiation pattern in Figure 4 reveals that the antenna exhibits a four-lobed (cloverleaf) radiation structure in the horizontal plane. The main lobes are observed at approximately 0°, 90°, 180°, and 270°, with gain values peaking around -5.751 dBi. While the negative gain indicates lower efficiency in this plane than the elevation pattern, the symmetric lobes ensure that the antenna provides directional diversity across four quadrants. This is useful in mobile applications where signals may arrive from multiple directions. The lobes in the azimuth plane ensure partial omnidirectional coverage, although nulls represent weaker signal regions around the lobes at about 45°, 135°, 225°, and 310°, respectively. This non-uniform azimuthal gain distribution limits the antenna's use in scenarios demanding truly isotropic performance. Moreover, the low azimuth gain complements the stronger elevation gain, illustrating that the antenna is primarily designed to radiate in directions out of its plane, which aligns with the typical behavior of ASAs. The azimuth in Mohamad *et al.* (2015), confirms bidirectional radiation in the unbacked state, equal forward and backward lobes, and a pronounced single forward lobe when backed by FSS. This indicates a stable, forward-focused azimuthal response post-reflector.

3. Conclusion

The analysis of the ASA reveals a characteristic bidirectional radiation profile with a figure-eight elevation pattern and a nearly omnidirectional azimuth pattern. The antenna exhibits a maximum and minimum gains of 5.48 and -5.75 dB perpendicular to the spiral planes. These patterns reflect the inherent symmetry and broadband nature of unbacked ASAs, supporting dual circular polarization in opposite hemispheres. The current design is therefore best suited for applications requiring wideband, bidirectional, and polarization-diverse performance, such as direction-finding, sensing, or near-field communications, rather than long-range directional links.

4. Recommendation

To improve the nearly omnidirectional, hemispherical 3D radiation pattern and gain while preserving its broadband and circular polarization capabilities, the number of turns and arms, as well as the spacing and material properties, should be optimized to achieve a significant enhancement.

Declarations

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Ethics Approval

Write Not applicable only when appropriate.

Conflicts of Interest

The authors declare no conflict of interest.

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