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Original Research Paper

Plasma-Based Beamforming Antennas

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ABSTRACT

In this article, beamforming methodologies for antennas are first reviewed, highlighting the pros and cons of each method. It is observed that each method offers unique advantages and limitations. Some of the key technologies used to provide beamforming antennas are also compared with consideration of complexity, beamwidth, price, scanning angle, frequency range, beamforming speed, and accuracy. It is shown that beamforming using plasma offers flexibility compared to other techniques while remaining relatively cost-efficient. Moreover, using plasma components, it is possible to conceal the entire antenna or parts of it. Based on these advantages, this study presents a low-complexity, low-cost plasma-based antenna for beamforming. This novel antenna combines an axial mode helical antenna surrounded by circular arrays of plasma elements, forming plasma cups around the helix. The power to energize the plasma elements is supplied by a set of converters and switches. The state of each switch is independently managed by a microcontroller, thereby enabling plasma elements to be individually switched ON or OFF. The plasma cups are used to control the direction and width of the radiated beam of the helix. Activation of a plasma cup enhances the beamwidth of the helix, while asymmetrically activated configurations allow for steering the end-fire beam pattern up to ±27°. The height of the plasma cups is smaller than the height of the helix, ensuring no increase in the overall height of the antenna. A prototype of the proposed antenna structure has been fabricated based on commercially available tools, and measurements for different configurations of the plasma reflectors have been carried out. The concept and computational results have been validated by the strong agreement between the simulation and measurement results. The proposed antenna offers a cost-effective solution for scanning and target acquisition in space communications and radar systems.

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1. INTRODUCTION

Antennas equipped with beamforming capabilities play an important role in wireless communication by providing dynamic control over signal directionality and shaping. These advanced antennas enhance the efficiency and reliability of wireless networks, optimizing signal transmission and reception. Beamforming technology has found widespread applications in various fields, including wireless networks, satellite communications, radar systems, and autonomous vehicles .

Numerous beamforming methods have been explored, each offering unique advantages and limitations [1-8]. Recent advancements in beamforming leverage novel materials with adjustable electromagnetic (EM) properties. Real-time adjustments of these materials enable dynamic control over antenna radiation characteristics, allowing precise manipulation of beam direction and shape. This approach is particularly valuable for applications requiring rapid and accurate beamforming, despite potential challenges related to bandwidth and steering.

In recent years, plasma materials have attracted significant attention due to their unique electromagnetic properties, that enable dynamic reconfigurability in antenna systems. Early studies, such as those by Borg et al. [9] and Rayner et al. [10], explored plasma as an efficient radiating element, demonstrating its potential for agile frequency control and tunability. Later, Anderson investigated plasma-based steerable antennas using the concept of plasma windowing [11], and Ja'afar et al. further implemented it at 4.9 GHz [12]. Subsequently, Wang et al. [13] modified the conventional plasma window antenna, transforming it into an end-fire plasma array antenna to enhance directional control. These studies highlighted the compactness and scalability of steerable plasma antennas but noted limitations such as narrow bandwidth and beam steering restricted to the azimuthal plane.

Malhat et al. [14] introduced a hybrid plasma-phased array system, combining electronic and plasma tuning mechanisms to achieve wide-angle steering, albeit with increased system complexity. More recent work by Mansutti et al. [15] and Magarotto et al. [16] explored intelligent reflective surfaces with enhanced steering precision, though these designs remain unimplemented and face practical challenges.

Building on these advancements, some of the authors previously proposed a 3D beam-steerable antenna [17,18] that utilizes a circular array of plasma reflectors in the form of a cup and an end-fire helical antenna. The design allows dynamic control of the beamwidth (37°–50°) and beam direction (±6° in 3D space) while maintaining structural simplicity and cost-effectiveness. However, the structure exhibits limitations in its steering range.

To address these limitations, this study proposes an improved design that introduces additional rows of plasma cups encircling the radiating helical antenna. As a result, it significantly enhances the steering range while preserving simplicity and affordability. The objective is to present this modified antenna and demonstrate its extended steering capabilities.

While the proposed design focuses on utilizing plasma materials for beamforming, it is important to compare this approach with other beamforming methods. By evaluating and contrasting these methods with plasma-based beamforming, the strengths and challenges of this innovative approach can be clearly understood. To this end, Section 2 provides a comparative analysis of different beamforming methods and technologies. Section 3 reviews the theoretical characteristics of plasma as an innovative technology for facilitating beamforming antennas. Section 4 presents a comprehensive investigation, including numerical simulations and experimental validations of a prototype beamforming antenna based on plasma material. Finally, Section 5 summarizes and concludes this study.

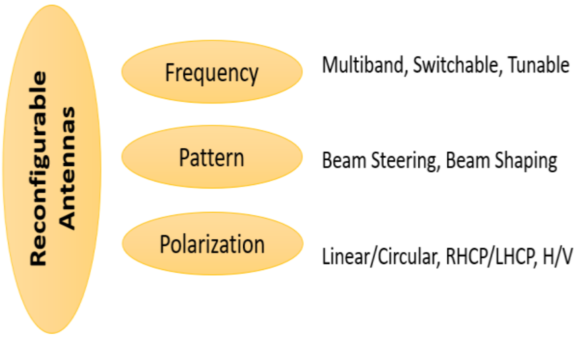


Fig. 1. Categorization of reconfigurable antennas.

2. BEAMFORMING METHODS

The rapid advancement of wireless technology has ignited a growing demand for versatile beamforming antennas. These antennas, valued for their reduced complexity and cost compared to traditional phased array systems, have gained significant attention in the ever-evolving landscape of wireless communication [19].

The term "reconfigurable antenna" refers to antennas designed to dynamically adjust parameters such as frequency, radiation pattern, or polarization, as depicted in Fig. 1. In the realm of space communication antennas, beamforming methods play a critical role in enabling efficient communication between ground stations and satellites or spacecraft. Specifically, an antenna falls into the category of beamforming antennas when it is capable of dynamically shaping or steering the radiation pattern to focus energy in desired directions, thereby enhancing communication performance.

Beamforming antennas contribute significantly to the success of both 5G, 6G, and satellite communications by optimizing signal transmission, enhancing network capacity, and adapting to the dynamic requirements of modern communication systems.

As depicted in Fig. 2, notable innovations have emerged to produce beamforming antennas. These innovations include electrical methods involving switches in the antenna structure, optical methods using photoconductive materials, structural alterations in the antenna configuration, and the incorporation of novel materials such as ferrites and plasmas into the antenna structure [23-26].

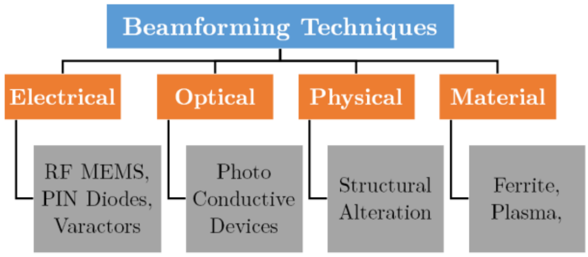


Fig. 2. Beamforming methods in antennas.

Table 1. Comparison between the features of beamforming methods in antennas: L (Low), M (Medium), H (High), and V (Variable).

Method / Feature	Electrical	Optical	Physical	Material based
Response time	V	L	H	M
Stability	H	V	V	V
Complexity	M	L	M	M
Price	V	M	M	V
Power consumption	M	L	M	L

Table 2. Comparison between different technologies of beamforming.

Technology	Complexity	Beamwidth	Price	Scanning Angle	Frequency Range	Velocity of Steering	Accuracy
Phased Array Antennas	Moderate to High	Fixed	High	Wide	Wide	Fast	High
Metamaterial Antennas	High	Fixed	Can vary	Limited	Wide	Moderate	High
Liquid Crystal Antennas	Moderate	Flexible	Moderate	Limited	Limited	Moderate	Moderat e
Plasma Antennas	Moderate	Flexible	Low	Wide	Wide	Fast	Moderat e

A comparative analysis between the beamforming methods in antennas is presented in Table 1, utilizing acronyms to denote the levels of Low (L), Medium (M), and High (H). In this table, the reconfigurability of electrical, optical, physical, and material-based methods is highlighted, with considerations for response time, stability, complexity, price, and power consumption. This comparison provides insights into the trade-offs associated with different approaches, guiding the selection of an appropriate method based on specific application requirements.

For better understanding, some of the key technologies to provide beamforming antennas, including phased array antennas [27-30], metamaterial-based structures [31,32], liquid crystal-based antennas [33–36], and antennas based on plasma material [37-44], are compared and the results are presented in Table 2. The comparison considerations include complexity, beamwidth, price, scanning angle, frequency range, beamforming speed, and accuracy in this table.

Each technology offers unique advantages and limitations. For instance, phased arrays provide fast and precise beam steering but suffer from fixed beamwidth, high complexity and cost, and susceptibility to grating lobes [45] and [46]. As a specific implementation of phased arrays, Butler matrix-based beamforming networks [47] offer a compact and efficient solution for mm-wave beam-steering, achieving wide scanning angles (~94°) and moderate beamwidths; however, they are more suitable for applications in high-frequency ranges (e.g. Ka-band) and face challenges related to broadband impedance matching, fixed beamwidth, and practical robustness.

Metamaterial-based structures utilize engineered artificial materials with extraordinary EM properties but face complexity in design, fabrication, and integration with practical systems and usually limited operating bandwidth [48].

Liquid crystal-based antennas provide another method for beamforming, utilizing the properties of liquid crystals to dynamically control the radiation pattern and polarization of the antenna. This technology offers advantages such as relatively fast response time and low power consumption. However, challenges include complexity in driving mechanisms and limited scanning angle and bandwidth compared to other methods [49].

Beamforming using plasma offers flexibility compared to other techniques while remaining relatively cost-efficient. An additional advantage is that plasma components can be electrically switched ON/OFF, allowing the entire antenna or parts of it to be concealed [50-57]. Based on these advantages, the following section presents the concept of plasma technology, and subsequently, a plasma-based beamforming antenna is introduced.

3. PLASMA TECHNOLOGY CONCEPT

To investigate the effect of plasma media on the radiation characteristics of antennas, it's essential to understand some basic properties of plasma. The complex permittivity ε_p of an isotropic plasma, which is a dispersive medium, under low-pressure conditions, can be modeled as [50-51]:

$$\frac{\varepsilon_p}{\varepsilon_0} = 1 - \frac{\omega_p^2}{\omega^2 + j\omega\upsilon} \tag{1}$$

where ω is the operating angular frequency in rad/s, v is the electron-neutral collision frequency in Hz, ε_0 is the free-space permittivity, and ω_p is the plasma angular frequency in rad/s, defined as [58]:

$$\omega_p = \sqrt{\frac{ne^2}{m\varepsilon_0}} \tag{2}$$

Here, n represents the electron density in m^{-3}, e is the charge of the electron, and m is the electron mass in Kg.

It is important to note that the plasma frequency can be adjusted by altering plasma characteristics such as density, allowing adjustment of the frequency band in which the plasma operates as a dielectric or as a conductor. For instance, for an incident EM wave with a frequency greater than the plasma frequency, the plasma medium behaves as a dielectric with positive permittivity, allowing the propagation of the incident wave through plasma.

Conversely, at frequencies lower than the plasma frequency, the plasma exhibits negative permittivity, prohibiting the propagation of the EM wave. At frequencies significantly lower than the plasma frequency, the plasma medium can act as a conductor, albeit not a very good one.

The electrical conductivity σ of plasma is determined by [50]:

$$\sigma = \left(\frac{\varepsilon_0 \upsilon \omega_p^2}{\upsilon^2 + \omega^2}\right) - j\left(\frac{\varepsilon_0 \omega \omega_p^2}{\upsilon^2 + \omega^2}\right) \tag{3}$$

This relation shows that the electrical conductivity of a plasma medium at a specific operating frequency can also be controlled by varying the plasma frequency, or collision frequency. The loss tangent $\tan\delta$ of the plasma can be derived from the ratio of the imaginary part of plasma permittivity to its real part as [58]:

$$\tan\delta = \frac{\mathrm{Im}(\varepsilon_p)}{\mathrm{Re}(\varepsilon_p)} = \frac{-\left(\frac{\omega_p^2 \nu}{\omega(\omega^2+\nu^2)}\right)}{\left(1-\frac{\omega_p^2}{\omega^2+\nu^2}\right)} = -\frac{\nu\omega_p^2}{\omega(\omega^2+\nu^2-\omega_p^2)} \tag{4}$$

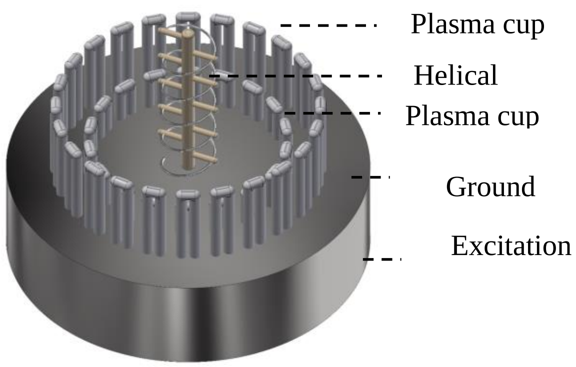
This expression indicates that plasma loss is influenced by the plasma parameters, and changes at different operating and plasma frequencies.

4. CASE STUDY

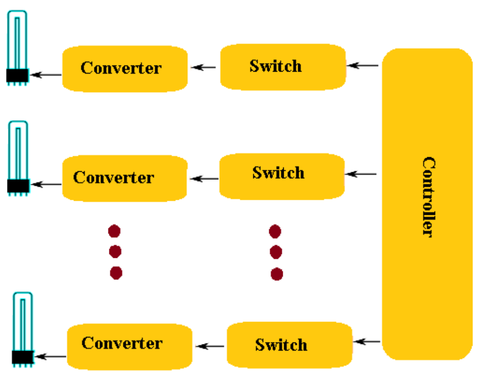
To demonstrate the potential of plasma in beamforming applications, this section presents a flexible and cost-efficient beamforming antenna based on plasma technology. The antenna can both steer the radiated beam and control its beamwidth. The first part of this section details the structure of the antenna. This is followed by the numerical study of the radiation characteristics of the antenna, and then the experimental validation is presented.

4.1 Antenna Structure

The antenna configuration, shown in Fig. 3(a), consists of an axial mode helical antenna which is surrounded by two concentric plasma cups. As shown in the figure, each plasma cup is formed by a dense array of U-shaped plasma tubes. Plasma media can generally be created by ionizing a gas using methods such as DC biasing, RF excitation, or microwave ionization [44]. In this study, the power to energize the plasma tubes is supplied by a set of electrical ballasts functioning as converters, while each converter is connected to a switch. The state of each switch is independently managed by a microcontroller, thereby enabling plasma tubes to be individually switched ON or OFF. Figure 3(b) illustrates the block diagram of this control setup, showing the plasma tubes and the corresponding electronic devices.



(a)



(b)

Fig. 3. (a) Three-dimensional view and the details of the antenna with two plasma cups, (b) Block diagram of the controlling circuit of plasma tubes.

The plasma and collision frequencies of the tubes are respectively f_p = 7.8 GHz and ν = 1 GHz. Note that, in this study, energizing half of the adjacent plasma elements, known as "half-cup", is what steers the radiated beam of the helical antenna. Dimensions of the half-cup, including its height (H_C) and diameter (D_C), are crucial in the determination of the steering range.

Dimensions of the helical section of the antenna for operating at a center frequency of 927 MHz are as follows: Diameter D_{Helix} = 114 mm (0.35λ), pitch angle α = 13.6°, height H_{Helix} = 544 mm (1.68λ), and N = 6.25 turns. The ground plane diameter is D_g = 480 mm.

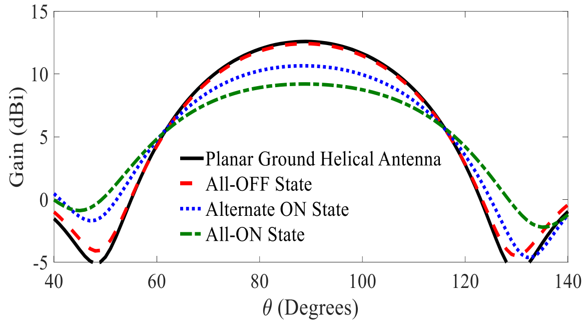


Fig. 4. Simulated radiation gain of the helical antenna surrounded by a single plasma cup.

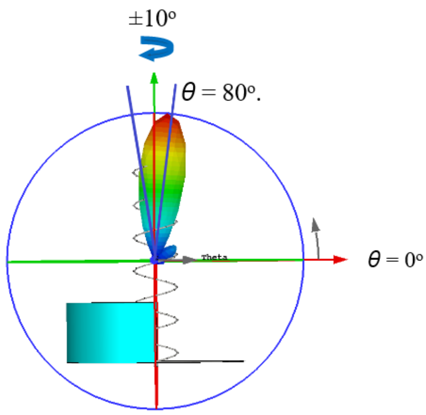


Fig. 5. Simulated ultimate steered radiated beam of one plasma half-cup around the helical antenna.

4.2 Numerical Investigation

A commercial full-wave numerical modeling tool based on the finite difference time domain (FDTD) method is used to assess the performance of the proposed antenna. Numerical EM simulations of the helical antenna with a ground plane (without plasma cups), serving as the reference antenna, reveal a radiation gain of approximately 12.6 dBi and a half-power beamwidth (HPBW) of 38.7° at θ = 90°. As was discussed previously in [17] and [18], a single plasma cup controls the beamwidth of the helical antenna. Figure 4 illustrates the radiated gain of the antenna with different numbers and arrangements of activated plasma elements when the height H_{c1} = 160 mm (~ 0.5 λ) and diameter D_{c1} = 330 mm (~ λ). When all elements are turned off (All-OFF state), a relatively narrow (38.7°) radiated beam identical to the beam of the helical antenna is observed. Activating all plasma elements (All-ON state) widens the beam from 38.7° to 50.3°. Intermediate activation (Alternate state) yields a beamwidth between the All-OFF and All-ON states. Generally, increasing the number of activated plasma elements widens the beam.

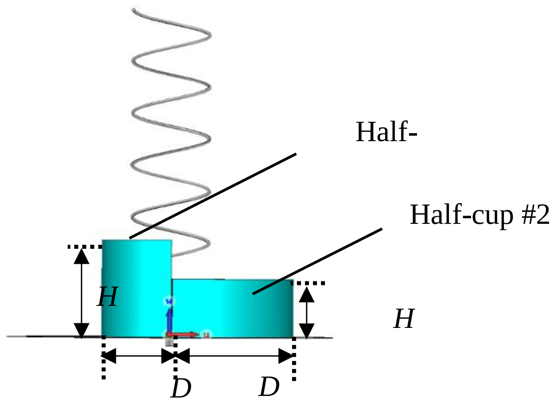


Fig. 6. Details of the antenna, while two plasma half cups with different diameters and heights are excited in opposite directions.

Unsymmetrical activation of the cup elements (resulting in a half-cup) steers the radiated beam of the helix, as depicted in Fig. 5, and alters the direction of its radiated beam within a solid angle of up to ±10 degrees. This mode allows for steering the antenna beam in the end-fire direction, with the scanning angle determined by the height and radius of the plasma cup. However, utilizing only one half-cup restricts the steering range. To enhance it, a second plasma half-cup positioned opposite the initial one, as illustrated in Fig. 6 is used. This configuration effectively modifies the direction of the radiated beam. Fig. 7 illustrates the simulated pattern of the helical antenna using two half-cups for H_{C1} = 0.5 λ, D_{C1} = 0.5 λ, H_{C2} = 1.3 λ and D_{C2} = 1.05 λ. The results show ±27° steering in the radiation pattern. The results presented in [42] examine the influence of the dimensions of the second half-cup on the radiation characteristics of this antenna.

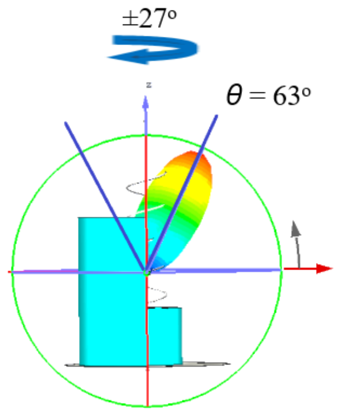


Fig. 7. The simulated radiation pattern of the antenna with two plasma haf-cups for HC1 = 0.5 λ, DC1 = 0.5 λ, HC2 = 1.3 λ and DC2 = 1.05 λ.

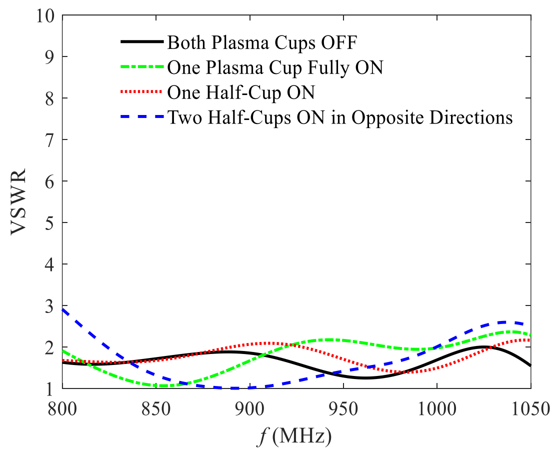
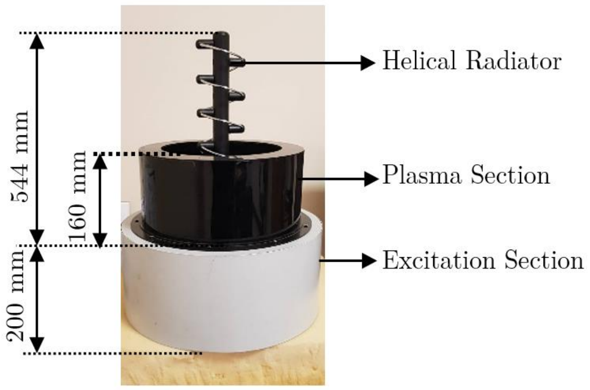


Fig. 8. Simulated VSWR of the antenna across different configurations of the plasma cup reflectors.

Although the utilized helical antenna is inherently designed to operate over a wide frequency range with good impedance matching due to its structural features, it is important to investigate the effects of the plasma reflectors on the impedance matching of the antenna. To this aim, Fig. 8 illustrates the effects of the plasma reflectors under four different configurations on the Voltage Standing Wave Ratio (VSWR) graph of the antenna: *a*) both plasma cups OFF, *b*) one plasma cup fully ON, *c*) one half-cup ON, and *d*) two half-cups ON in opposite directions. The results show minimal variation in VSWR across different scenarios because the plasma reflectors handle only small current densities.



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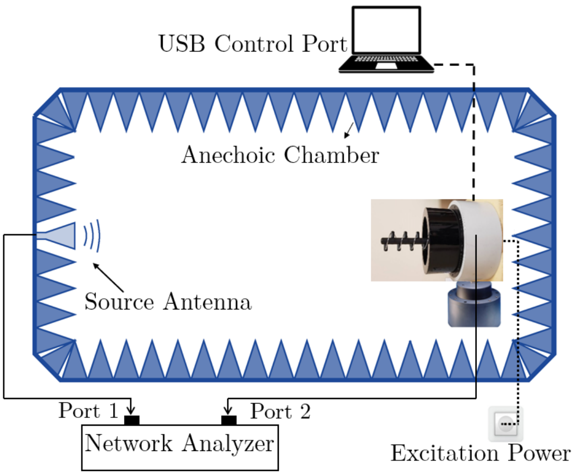


(b)

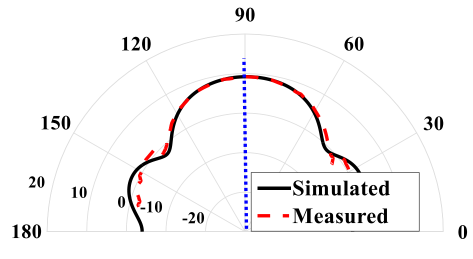
Fig. 9. (a) Fabricated prototype antenna using a single plasma cup and details of its dimensions, (b) measurement setup.

5. EXPERIMENTAL VALIDATION

For experimental validation, a prototype of the proposed antenna using a single plasma cup for operation at a frequency of f = 927 MHz is fabricated, as shown in Fig. 9. The height and diameter of the first plasma cup are H_{c1} = 160 mm and D_{c1} = 330 mm, respectively. The height and diameter of the second cup are set to H_{c2} = 0 mm and D_{c2} = 0 mm. The measurements are performed in an anechoic chamber with a peak gain accuracy better than 0.5 dBi within the operating frequency range of the antenna. The measurement setup is illustrated in Fig. 9(b). In this setup, two connections for energizing the excitation section of the antenna and also a USB port as a user interface are illustrated.

A series of measurements are conducted, and a comparison between the simulated and measured results is presented.

Figure 10 compares the simulated and measured radiation gain of the antenna for various plasma reflector configurations, showing good agreement between simulated and measured results. In summary, the proposed method for beamwidth control and beam steering using a reflector in the form of a plasma cup is validated both numerically and experimentally.



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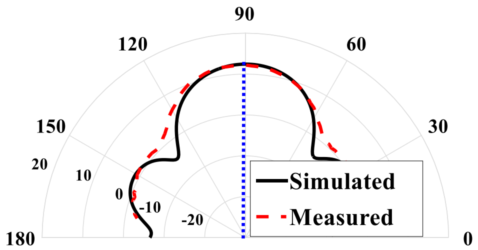

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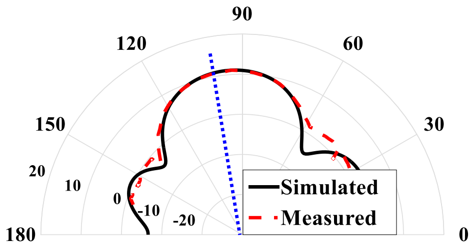

(c)

Fig. 10. Comparison between the simulated and measured radiation gain of the antenna in different modes: (a) ALL-ON states, (b) ALL-OFF states, (c) Half-cup.

6. CONCLUSION

In this paper, dynamic beamforming of the radiated beam from a helical antenna has been demonstrated. it has been shown through full-wave EM simulations that plasma cups around the helical antenna can electronically alter both the direction and width of the radiated beam. Asymmetrically activated configurations allow for steering the end-fire beam pattern of the helical antenna up to 54°.

A prototype has been fabricated and tested in L-band frequency, validating the concept and computational results through good agreement between simulation and measurement data. This cost-effective method offers the potential for scanning and detecting targets in space communications and radar systems, utilizing the versatility of plasma materials

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest

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