Research Article

A REVIEW OF PLASMA ANTENNA TECHNOLOGY FOR SATELLITE COMMUNICATION

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Abstract. *In wireless communication systems, the antenna is the most crucial component. An antenna is a device that converts electrical impulses into radio waves and vice versa. Antennas come in a variety of shapes and sizes, with varying properties depending on the necessity for signal transmission and reception. In this study, we give a comparative analysis of the promise and limitations of plasma antennas in the field of satellite communication systems giving an in-depth investigation of their fundamental principles, technological breakthroughs, applications, and the obstacles that follow their integration.*

Keywords

Plasma antenna, satellite communication, Satellite signals, radio waves.

1. Introduction

The search for sophisticated, high-performing antennas that are resilient to unfavorable atmospheric conditions is what keeps pushing innovation in the large field of satellite communication technology. Within the contemporary communication landscape, satellite networks function as the foundation for worldwide connectivity, providing a wide range of vital services from weather tracking and disaster relief to telecommunications. However, a number of significant obstacles face satellite communication as the need for bandwidth-intensive applications keeps rising. The number of satellites has grown exponentially due to initiatives like satellite constellations for broadband internet access, which have caused the radio frequency spectrum to become extremely congested. The effectiveness and dependability of satellite communication systems are seriously hampered by this congestion, as well as by the intrinsic susceptibility of conventional metallic antennas to signal interference and their restricted capacity to adjust to shifting ambient conditions. Moreover, the already complicated web of satellite networks becomes even more sophisticated due to the constantly changing environment of communication technologies, which includes the introduction of new standards and protocols. The hunt for novel solutions in this ever-changing environment has prompted research and development initiatives aimed at developing next-generation antenna technology. Plasma antennas stand out among these as a promising option. Through the utilization of the distinct characteristics of ionized gas, plasma antennas present a revolutionary method for antenna design. The intrinsic versatility and flexibility of these antennas allows them to overcome the limits of conventional metallic antennas by optimizing signal transmission, mitigating interference, and dynamically adjusting their electromagnetic properties. Plasma antennas, an interesting substitute for traditional metallic antennas, are among the potential alternatives in this field. By using ionized gas, or plasma, as the radiating element, plasma antennas open up new possibilities for improving satellite communication systems. Because of the special qualities of plasma, namely its dynamic reconfigurability and adaptability, these antennas are attracting a lot of attention and research in the field of satellite communication [1]. The idea of using plasma for antennas was explored in 1919, with J. Hettinger's patent "Aerial Conductor for Wireless Signaling and Other Purposes" suggesting the transmission of electromagnetic (EM) signals. However, significant developments started gaining traction in the late 20th and early 21st centuries due to advancements in plasma physics and material science. Then researches intensified with advancements in plasma generation techniques, including radio-frequency (RF) and microwave plasma sources leading to significant progress in understanding plasma dynamics and optimizing antenna performance [2, 3, 4].

Ionized gas is used as an active antenna element, and this is the fundamental idea behind plasma antennas. A state of matter known as "plasma" is created when gases are sufficiently energetic to contain ionized positive particles and free-moving negatively charged electrons [5]. Plasma antennas rely on generating ionized gas, typically through the application of RF or microwave energy. This ionization can occur in various gases, including noble gases like argon or mixtures such as nitrogen and hydrogen. The ionized gas serves as the conductive element of the antenna. When ionized, the gas can reflect, refract, or radiate electromagnetic waves depending on its density and configuration. Plasma antennas can be designed in various shapes, such as cylinders, spheres, or planar geometries, to optimize radiation patterns and gain. Compared to their conventional metallic counterparts, plasma antennas are distinguished by their tunability and adaptability [6, 7, 8, 9, 10]. Reconfigurability is a benefit of plasma antennas over fixed-shape metallic antennas [11, 12, 13, 14, 15, 16]. By varying the ionization density, the electromagnetic properties of the plasma can be changed, allowing the antenna to dynamically modify its properties. In satellite communication, where operational requirements and environmental conditions frequently change and quick adjustments are needed for the best possible signal transmission, this feature is invaluable. Moreover, a notable benefit of plasma antennas is their flexibility in terms of frequency selection and radiation pattern modification [17, 18]. These antennas offer versatility in satellite communication applications by having the capacity to cover a wide range of frequencies. The flexibility of satellite systems is increased by their capacity to quickly change frequencies or modify radiation patterns, which may reduce interference and improve system capability and effectiveness. Plasma antennas have a variety of effects on satellite communication. The technology claims to solve a number of issues that traditional antennas have, such as spectrum congestion, signal interference, and a restricted ability to adjust to shifting communication needs. Plasma antennas have the potential to completely transform satellite communication and open the door to improved performance, robustness, and dependability in a world that is becoming more interconnected. This will usher in a new era of seamless international connectivity and communication.

The goal of this review is to provide a thorough analysis of the state of plasma antenna technology for satellite communication. This review attempts to provide a comprehensive understanding of the potential and limitations of plasma antennas in the field of satellite communication systems by means of an in-depth analysis of their underlying principles, technological advancements, applications, and the challenges that accompany their integration. Through an analysis of current literature, emerging trends, and potential future applications, this review seeks to advance the growing conversation about novel antenna technologies. In this paper, we explore the viability and benefits of plasma antennas across a wide range of frequency bands, from MHz to GHz. The MHz range, particularly between 30 MHz to 300 MHz, is crucial for specific satellite communication applications such as low Earth orbit (LEO) satellite systems, where plasma antennas demonstrate low noise and high reconfigurability. Conversely, the GHz range, especially from 1 GHz to 10 GHz, is essential for high-data-rate satellite communications, including geostationary orbit (GEO) satellites and modern broadband satellite networks. This diversity in frequency usage highlights the flexibility of plasma antennas to adapt to various operational requirements and environmental conditions, making them suitable for different satellite communication scenarios.

The remainder of this paper is organized as follows: section 2. elaborates on the consideration of the satellite antenna design and plasma antenna. Section 3. focuses on plasma antennas flexibility data rates and signal manipulation in the satellite communication. A discussion about current issues on gaseous plasma antenna in case of the satCom navigation system is presented in section 4. . The Potential of reconfigurability in smart plasma antenna for satellite application is discussed in section 5. . Section 6. is concentrated on plasma antenna array for receiving Galileo and GPS satellite signals. Finally, the paper concludes on section 7. .

2. Satellite antenna design consideration and plasma antenna

The passage highlights the unique positioning of transmitting antennas on Clark Orbit satellites, comparing their function to an "invisible tower" situated approximately 36,000 kilometers above the Earth's surface. This positioning eliminates crown reflections and minimizes interference from ground steel, affecting antenna noise temperature and backloading. The spacing of satellites in the Clark Orbit is crucial, impacting the design of both the satellites and Earth station antennas, as reduced spacing allows for more satellites in orbit. However, the challenge arises in the normalization of the full orbit, especially when satellites operate on different frequencies. The objective is to permit closer spacing between satellites while ensuring that North American satellites, sharing the same frequencies, can use alternate linear polarization techniques [19]. Regarding the integration of plasma antennas into this context, they could potentially offer distinct advantages. Plasma antennas have demonstrated higher signal-to-noise ratio compared to traditional metal antennas at satellite frequencies [20]. The ability to manipulate the plasma properties allows for control over the polarization of the transmitted RF waves. There could tuning in polarization characteristics, such as shifting between horizontal and vertical polarization or altering the phase relationships between signals, plasma antennas can effectively implement alternate linear polarization strategies. The work by [21] introduces a novel type of plasma antenna fabricated using flexible materials and excited by a 520 kHz alternating current (AC) power supply. The research focuses on investigating the reconfigurability and characteristics of this flexible plasma antenna, with a particular emphasis on its shape and discharge parameters. The article discusses how varying the antenna's shape from a monopole to a helix configuration allows for rapid and easy control of antenna characteristics, including impedance, reflection coefficient, radiation pattern, and gain. Fig 1 demonstrates the versatility and reconfigurability of a flexible plasma antenna by comparing its performance in different configurations. The reflection coefficients (S11) in Figure 1(a) indicate the efficiency of impedance matching, with the Monopole configuration showing significant dips at certain frequencies, suggesting better matching and radiation efficiency. Figure 1(b) illustrates the relative gains (S21) for the Monopole and Helix configurations, revealing that the Monopole configuration has higher gains across the frequency range, particularly between 100 MHz and 300 MHz. The radiation pattern in Figure 1(c) shows the directional distribution of radiated power at 250 MHz for two different distances, with the pattern becoming more directional at a greater distance (25 cm). Figure 1(d) highlights the axial ratio (AR), indicating the polarization purity, with the Helix configuration achieving lower AR values over a range of angles, suggesting superior circular polarization performance. Moreover, it highlights the potential for adjusting antenna polarization by altering its shape. In case of interferences that could be an issue, this work by [5] proposes plasma antennas within the frequency range of 30 MHz to 1500 MHz. These antennas use a novel approach to a solution to mitigate co-site interference involves using a plasma shield, an array of plasma discharge tubes surrounding an antenna. By adjusting the discharge current in the shield, it selectively reflects lower frequency interfering signals, allowing the desired signals to pass through, effectively mitigating co-site interference. This allows for more efficient frequency reuse and better isolation between channels or users on the same frequency band, avoiding interferences in satellite conditions.

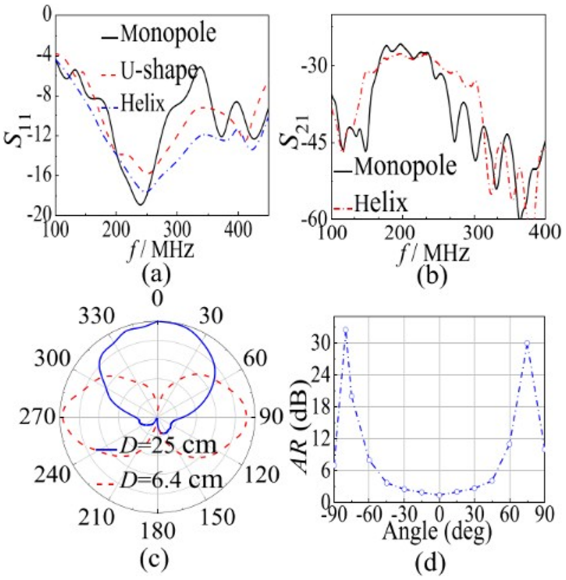

Fig. 1: Characteristics of the flexible plasma antenna. (a) Reflection coefficients (S_{11}), (b) relative gains (S_{21}), (c) radiation pattern at working frequency 250 MHz, and (d) axial ratio at working frequency 250 MHz.

Another work [22] reiterates the plasma antenna's potential for reconfigurability and a decreased radar cross-section, which offers advantages in terms of shape, frequency, and quick adaptation in microsecond timescales. The behavior of plasma as a dielectric, transmitting electromagnetic waves above its plasma frequency, is explained in detail by theoretical in-sights. The study explains how surface wave dispersion in cylindrical geometry demonstrates the special capacity of plasma to sustain wave modes along the plasma-dielectric interface. Comprehensive experimental results are presented in the study. After a thorough analysis, the efficiency and noise characteristics of the plasma antenna are shown to be highly promising [Fig. 2], with low noise levels appropriate for broadcast communications. Figure 2 compares the high-frequency (HF) noise spectra of different antenna types, emphasizing the potential advantages of plasma antennas. Figure 2(a) shows the noise spectra for a plasma antenna driven by a 50 Hz AC current, with fluctuating noise levels and peaks at specific frequencies. In contrast, Figure 2(b) displays the noise spectra for a plasma antenna driven by surface wave (SW) RF, demonstrating significantly lower noise levels and a prominent peak around 20 MHz. Figure 2(c) presents the noise spectra for a traditional metal antenna, which exhibits a single prominent peak around 20 MHz with lower noise levels across other frequencies. In addition to the pioneering research discussed earlier, recent studies have made significant strides in enhancing the capabilities of plasma antennas for satellite communication systems. Adaptive beamforming techniques have been explored to dynamically adjust the directionality of satellite antennas, optimizing signal reception and transmission efficiency. These smart antennas, equipped with adaptive algorithms, not only mitigate interference but also improve overall communication reliability in satellite environments [23]. Moreover, advancements in frequency reconfigurability have demonstrated the ability of plasma antennas to dynamically tune to various frequency bands by manipulating plasma parameters. This capability is crucial for modern satellite systems that operate across diverse frequency ranges, ensuring optimal performance under varying communication scenarios [24]. Further innovation is evident in the design of multi-polarized plasma antennas, where sophisticated RF power supplies and precise discharge tube configurations enable rapid re-configuration of antenna impedance, radiation patterns, and polarization states. This flexibility is particularly advantageous in satellite applications where environmental conditions and communication requirements fluctuate unpredictably [25]. Additionally, the development of hybrid metal-plasma Yagi-Uda antennas represents a significant breakthrough. By integrating plasma elements alongside traditional metal components, these antennas maintain the high gain and directivity characteristic of Yagi-Uda designs while adding the adaptability of plasma technology. Such hybrid designs are poised to revolutionize satellite antenna systems by offering robust performance and versatility in dynamically changing satellite communication environments [26]. The integration of plasma antennas in satellite communication systems addresses specific frequency ranges to optimize performance. For instance, in the 100 MHz to 300 MHz range, plasma antennas offer enhanced impedance matching and radiation efficiency, as demonstrated by their monopole configuration. This frequency band is particularly relevant for applications requiring robust signal transmission with low interference, such as certain LEO satellites. The ability of plasma antennas to switch between different polarization states at these frequencies also provides a strategic advantage in mitigating interference and improving signal quality.

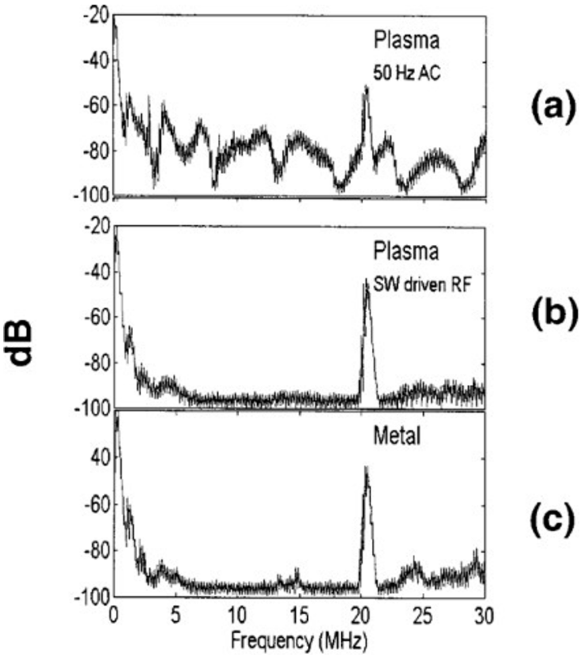

Fig. 2: hf noise spectra received by: (a) a 50 Hz ac current driven fluorescent tube, (b) a surface wave driven plasma Antenna, and (c) a metal Antenna.

Distinct from the idea of plasma antennas for satellite communication is the work on downsizing of microwave planar circuits [27] employing composite microstrip/coplanar-waveguide transmission lines. However, in the larger context of satellite systems and wireless communication, both fields can be pertinent and contribute to advances in RF/microwave technology. The goal of the miniaturization article is to enhance the functionality and minimize the dimensions of conventional microwave planar circuits, particularly filters and power dividers. The suggested method uses CM/CPW lines, a special type of transmission line architecture, to reduce size significantly without sacrificing functionality. However, ionized gas, or plasma, is used as an antenna element in satellite communication plasma antennas. This technique investigates the dynamic manipulation of the plasma state to modify the characteristics of the antenna, including frequency tunning and reconfigurability. The paper discusses the miniaturization of microwave planar circuits, specifically highlighting on power dividers and filters. The proposed approach includes a novel technique called composite microstrip/coplanar-waveguide transmission lines (CM/CPW lines). These lines, consolidated on a single dielectric substrate, aim to obtain circuit miniaturization by combining the characteristics of microstrip lines (MLs) and coplanar waveguide (CPW) lines. The study describes a significant physical length reduction, up to 80.8% after zigzagging the CM/CPW line. The proof of concept design example of a two-way Wilkinson power divider (WPD) shows promising results, with a size reduction factor of 86.9% compared to conventional designs while maintaining a fractional bandwidth of 57.7% for the WPD. In summary, the research examines a new transmission line approach to increase miniaturization in microwave planar circuits, addressing the demand for high-performance and compact RF/microwave components in modern communication systems.

3. Plasma antennas flexibility data rates and signal manipulation in the satellite communication

Plasma antennas offer significant advantages in satellite communication, particularly regarding reduced thermal noise and higher data rates at satellite frequencies. Plasma antennas with plasma feeds—such as plasma waveguides and coaxial cables—paired with low-noise receivers, can achieve higher data rates compared to their metal antenna counterparts [4]. The reduced thermal noise in plasma antennas is attributed to the unique properties of plasma, which can be manipulated to minimize noise levels. Unlike metal antennas, where thermal noise is inherent to the conductive material, plasma antennas use ionized gas to conduct signals. This ionized state can be controlled to reduce noise, improving the signal-to-noise ratio (SNR) and thereby enhancing data rates, especially at high-frequency bands used in satellite communications. In satellite communication, maintaining a high SNR is crucial for reliable data transmission over vast distances. The lower thermal noise of plasma antennas makes them particularly suitable for satellite uplinks and downlinks, where signal integrity is paramount. Higher data rates are also essential for modern satellite applications, including high-definition broadcasting, internet services, and real-time data transfer, all of which can benefit from the enhanced performance of plasma antennas. This book [4] discusses the principles behind plasma antennas, emphasizing their capability to manipulate electromagnetic waves through reflective and refractive modes, which are dependent on plasma density or frequency. Plasma antennas can steer and focus RF signals without the need for phased arrays, presenting substantial benefits for satellite communication. These benefits are applicable to both fixed installations (e.g., DIRECTV) and mobile platforms (e.g., vehicles or aircraft). Plasma antennas' ability to operate efficiently in the GHz range, particularly between 1 GHz to 10 GHz, makes them highly suitable for high-data-rate satellite communications. This frequency band is critical for modern satellite applications like broadband internet services, high-definition broadcasting, and real-time data transfer. Plasma antennas in this range benefit from lower thermal noise and higher signal-to-noise ratios, which are essential for maintaining reliable communication links over vast distances. Additionally, the dynamic reconfigurability of plasma antennas allows for precise beam steering and frequency tuning, enhancing overall system performance and adaptability in varying operational environments. The steering of antenna beams in plasma antennas is primarily achieved through the physics of refraction. When an electromagnetic wave passes through a plasma medium, its path can be bent or refracted due to changes in plasma density. By dynamically adjusting the density of the plasma, the direction of the refracted wave can be controlled, allowing for precise beam steering. This method eliminates the need for mechanical movement or complex phased array systems, providing a more flexible and responsive solution for directing signals. For satellite communication, the ability to steer beams without mechanical components reduces the weight and complexity of satellite payloads, leading to cost savings and increased reliability. Beam steering is essential for targeting specific ground stations, managing multiple communication channels, and adapting to changing operational requirements in real time. Furthermore, plasma antennas can function as reflectors and lenses, allowing them to act as both convergent and divergent tools. These capabilities are crucial for altering beam widths, thereby enhancing the range and directivity of the antenna. However, it is essential to conduct further research to explore the effects of plasma density fluctuations on practical prototypes.

4. Gaseous plasma antenna in case of Satcom navigation system

In order to determine the possible integration of GPS antenna arrays with stacked Gaseous Plasma Antennas into applications for Global Navigation Satellite System (GNSS), an analysis is performed comparing two separate antennas elements that are curled and turnstile [Fig. 3]. The study assesses the reflection coefficient, axial factor and maximal gain of these antennas. Plasma discharges with specific parameters are relied upon by both antennas. The study assesses the reflection coefficient, axial factor, and maximal gain of these antennas. Plasma discharges with specific pa-

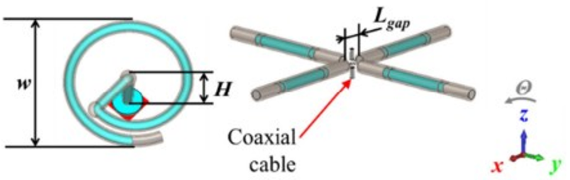

Fig. 3: Schematic of the curl antenna (left) and of the turnstile antenna (right).

rameters are relied upon by both antennas. The evaluation of the curl antenna's performance is based on its axial ratio, gain, input impedance, and reflection coefficient. The outcomes demonstrate a respectable an-gular breadth for both circular polarization and impedance matching. On the other hand, the turnstile antenna exhibits superior impedance matching but is limited in its operational frequency range, mainly because the resonance frequency is affected by the diameters of the electrodes. Although it has a greater gain and a wider axial ratio range, it is unable to function in the L-band frequency range needed for GNSS applications. The curl antenna's ability to achieve circular polarization within the L-band frequency range makes it an attractive choice for GNSS applications. Of the two antennas, it is the only one that meets GNSS criteria. Still, it needs to be improved for practical use. While the turnstile antenna exhibits benefits in terms of gain and compactness, its ability to operate above 1 GHz is restricted by technological limits related to electrode diameters. The analysis shows that GPA may be used in GNSS arrays, giving designers more leeway to create creative arrays that reduce multipath errors and maximize beam steering. Nonetheless, more investigation is required for the creation and enhancement of GPAs as well as their incorporation into workable GNSS systems [29].

Another research discusses the use of GPAs in SatCom, especially in GNSS systems. A basic design of an L-band plasma dipole is presented, and its performance is extensively assessed. A numerical and experimental technique was used. The concept is based on a plasma discharge prototype that was evaluated for plasma density. This method allows for the assessment of plasma properties that may be employed in numerical simulations. The plasma dipole resonates at 1.21 GHz, which corresponds to the L-band. Because plasma is a lossy medium, its gain is 3.8 dB lower than that of a metallic dipole. When the plasma is shut off, a drop of 15.2 dB is seen [Fig. 4], proving the capability of a plasma antenna of electrically disappearing. It is conceivable to use a plasma dipole in SatCom and space communications, but various improvements must be made, including reducing the size of the PPUs and the discharge, and increasing the plasma density within the sources [30].In satellite navigation systems, the L-band frequency range (1.0 GHz to 2.0 GHz) is crucial for GNSS applications. Plasma antennas operating in this band, such as the plasma dipole resonating at 1.21 GHz, demonstrate the potential for achieving circular polarization and maintaining high signal integrity. The ability to electrically disappear when not in use and the flexibility in design allow for innovative array configurations that can minimize multipath errors and optimize beam steering. These features are particularly advantageous for improving the accuracy and reliability of satellite navigation systems.

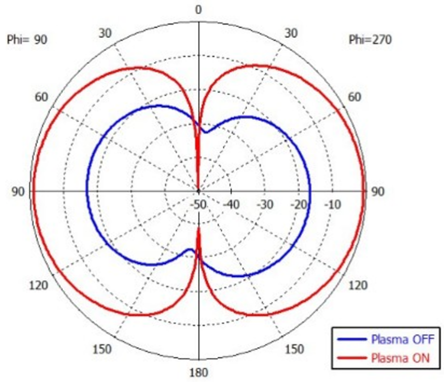

Fig. 4: Polar gain pattern of the plasma dipole when the plasma is ON (red curve), and OFF (blue curve).

An other paper [31] primarily focuses on improving the accuracy of navigation systems by integrating data from Global Navigation Satellite Systems (GNSS) with Inertial Measurement Units (IMU). Actual test results show that the proposed integrated navigation system is better than the traditional algorithm with more than 38% improvement in 3D position accuracy, 30% in 3D speed, 35% in roll, 44% in pitch, and 39% in heading. It addresses challenges related to urban environments and the limitations of traditional integrated algorithms. On the other hand, satellite communication involves the transmission of signals to and from satellites for various purposes, including telecommunications, broadcasting, and data relay. Plasma antennas, on the other hand, explore the use of ionized gas (plasma) as an antenna element, allowing for dynamic control of antenna properties.

5. Potential of reconfigurability in smart plasma antenna for satellite application

In order to capitalize on the idea of enveloping a plasma antenna in a controllable plasma blanket, the paper [32] presents experimental results on the radiation patterns and Voltage Standing Wave Ratio (VSWR) of a smart plasma antenna. The ability of plasma antennas to reduce co-site interference by sending high-frequency signals through lower frequency plasma antennas is investigated in this paper. This innovation aims to improve the initial design by increasing plasma density and minimizing the gaps between plasma tubes, thereby enhancing performance in radiation patterns and reducing VSWR.

This configuration's variation in plasma density makes it possible to change the antenna radiation and electronic steering in different directions. The paper also mentions the ongoing development of new electronics and controls to increase plasma density and discusses the excellence in VSWR measurements and radiation patterns achieved in the frequency range of 2 GHz to 3 GHz. Fig. 5 shows the VSWR with 10 of 12 plasma tubes turned on. The result of the VSWR is perfect; 1.24 at 2.64 GHz. The radiation pattern is measured in different directions, in the azimuthal direction the forward gain is about 8 dB and rear gain is about 20 dB. The gain can be significantly increased by using plasma lens focusing as the paper suggested. Additionally, it details the benefits of Ramsauer Townsend Effects, resulting in lower thermal noise compared to metal antennas at certain frequencies. It proposes applications in satellite plasma antennas, highlighting their lower thermal noise operation, possible use in refractive or reflective modes, and the potential for steering and focusing electromagnetic waves using controlled plasma densities. The flexibilities found in the smart plasma antenna are highly desirable for satellite application. Smart plasma antennas exhibit remarkable reconfigurability across different frequency bands, from MHz to GHz. In the 30 MHz to 1.5 GHz range, plasma antennas can effectively mitigate co-site interference by selectively reflecting lower-frequency interfering signals. This capability is essential for efficient frequency reuse and better isolation between channels in satellite communication systems. For higher frequencies in the GHz range, the rapid reconfiguration of antenna impedance and radiation patterns enhances the flexibility and efficiency of satellite communication networks, making plasma antennas a versatile solution for dynamic and high-performance satellite applications.

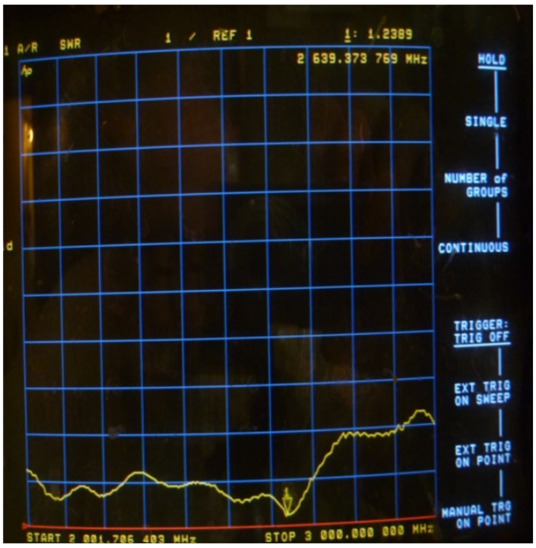

Fig. 5: VSWR of Smart Plasma Antenna with 10 of 12 plasma tubes ON. Frequency span from 2 GHz - 3 GHz. Lowest VSWR is 1.24 at 2.64 GHz. Reference (red line) is VSWR=1, with vertical scale of VSWR=1/div.

6. Plasma antenna array for receiving galileo and gps satellite signals

Gaseous Plasma Antennas (GPAs) are a type of antenna where ionized gas (plasma) is used as the conducting element instead of traditional metal structures. The plasma is produced inside dedicated sources, which consist of three main components: (i) a dielectric vessel, such as a glass cylinder, which confines a neutral gas, (ii) an excitation circuit, such as metal electrodes, which transports the electrical power required to ionize the gas and form the plasma, (iii) a signal processing unit. Because of the plasma is an electrically conductive medium, it can maintain the currents necessary to transmit and receive electromagnetic waves [33, 34]. These antennas exploit the unique properties of plasma to achieve various advantages over conventional antennas in terms of reconfigurability, adaptability, and performance under different operational conditions. One of the significant advantages of plasma antennas is their ability to dynamically adjust their characteristics. By controlling parameters such as the density of the plasma or the shape of the plasma cloud, the antenna's resonance frequency, radiation pattern, and polarization can be modified in real time. This capability makes plasma antennas suitable for adaptive and cognitive radio ap- plications where frequency and interference mitigation are crucial. Furthermore, plasma antennas can operate in extreme environmental conditions where traditional metallic antennas may suffer from corrosion or temperature limitations. The plasma can be maintained at a stable state over a wide range of temperatures and pressures, making these antennas potentially suitable for aerospace and space exploration applications. In addition, this technique is exceedingly fast, taking just milliseconds. Another intriguing feature of GPAs is that the reaction of a plasma to an impinging EM wave is frequency-dependent. As a result, GPAs are transparent to any signal with a fre-

Tab. 1: Summary of the related works.

Reference	Summary and Relevance
STARLET Project	Investigates the design and construction of Plasma Antenna Arrays (PAAs) utilizing plasma discharges in dielectric structures. These arrays offer reconfigurability in impedance, frequency, bandwidth, and directionality, crucial for optimizing satellite signal reception [34].
Radnovic, Ivana, Neˇsi´c, A., and Nesic, Dusan. (2014)	Explores printed antennas capable of circular polarization and tunable elevation angles, relevant for achieving optimal reception performmance in satellite communication [35].
P. Magnusson, "Antenna for GNSS Reception in GEO- Orbit," Royal Institute of Tech- nology, 2014.	Discusses antenna design considerations specific to GNSS reception in geostationary orbit, pertinent for enhancing signal acquisition from Galileo and GPS satellites [36].
Araszkiewicz, A., and Kiliszek, D.	Evaluates the impact of using GPS L2 receiver antenna corrections for Galileo E5a frequency on position estimates, highlighting the importance of accurate antenna phase center modeling for precise GNSS positioning [37].

quency greater than the plasma frequency. Therefore, interference levels between various GPAs can be extremely minimal, provided that the operation frequencies are correctly calibrated. Furthermore, by developing an appropriate on-off strategy that reduces the times when the antenna transmits or receives signals, the radar cross section may be significantly lowered. This property makes GPAs ideal for applications that require stealth. Finally, when the plasma is turned off, it returns to a neutral gas, converting GPAs into basic dielectric tubes that are transparent to incoming electromagnetic waves. Thus, GPAs may be stacked to produce ar- rays as long as co-site and/or parasitic interference levels are maintained under control [3].

The evolution of Gaseous Plasma Antennas (GPAs) was investigated [34], emphasizing their reconfigurable potential for use in satellite communication. The study describes in particular the STARLET project, which aims to build a Plasma Antenna Array (PAA) to receive signals from satellites that are part of Galileo and GPS. GPAs produce and receive electromagnetic waves using plasma discharges contained in dielectric tubes, in contrast to conventional metallic antennas. Their unique quality is that they have electrically tunable characteristics that can be changed in microsecond increments, including impedance, frequency, bandwidth, and directionality. This paper explores the design and construction of a non-planar antenna with multiple plasma discharges in a dielectric structure for electrical reconfigurability and smart signal processing. Using the ADAMANT code, it simulates the effects of variables such as plasma density, frequency range, and different configurations of plasma arrays in order to investigate the relationship between plasma parameters and antenna performance through numerical experiments. Numerical analysis results show that the behavior of the antenna is highly dependent on variations in plasma density. Lower densities change the gain pattern, while higher densities produce patterns more like those of conventional metallic antennas. The study also assesses various configurations for plasma arrays and finds that, in comparison to equivalent metallic arrays, radiated power can be improved by adjusting the plasma density.

The development of Plasma Antenna Arrays (PAAs) for satellite signal recep- tion from Galileo and GPS systems involves exploring cutting-edge technologies and methodologies. This section reviews key contributions and findings from related studies that inform the STARLET project's goals. Table 1 summaries these studies.

The STARLET project aims to leverage advancements in antenna technology, particularly Plasma Antenna Arrays (PAAs), to enhance satellite signal reception capabilities. The use of numerical simulations, such as those conducted with the ADAMANT code, demonstrates the influence of plasma density variations on antenna performance, crucial for achieving desired signal characteristics [34]. Additionally, insights from studies on printed antennas [35] and antenna design for GNSS reception in specific orbits [36] contribute to optimizing antenna con- figurations for improved performance in receiving Galileo and GPS signals. The study by Araszkiewicz and Kiliszek underscores the practical challenges associated with inaccurate antenna phase center corrections for Galileo frequencies, emphasizing the need for precise modeling to mitigate positioning errors [37]. The plasma antenna arrays designed for receiving Galileo and GPS signals operate effectively in the L-band (1.0 GHz to 2.0 GHz). These arrays demonstrate significant advantages in terms of gain and impedance matching, essential for reliable GNSS applications. The ability to achieve circular polarization within this frequency range ensures high precision and accuracy in satellite navigation, making plasma antennas an attractive choice for integration into GNSS systems. Further research and development will focus on enhancing these capabilities to fully realize the potential of plasma antennas in practical satellite navigation scenarios. Their findings underscore the necessity of precise modeling in antenna phase center corrections to mitigate errors which could lead to problems in case of receiving signals. This empirical evidence complements theoretical advancements in plasma antenna design and informs strategies for enhancing signal reception reliability in satellite communication systems.

7. Conclusion

The integration of plasma antennas into satellite communication systems presents a promising avenue for advancing antenna technology. Plasma antennas offer distinct advantages over traditional metal antennas, particularly in terms of reconfigurability, signal-to-noise ratio (SNR), and operational flexibility across satellite frequencies. Plasma antennas demonstrate superior SNR characteristics due to their ability to minimize thermal noise through controlled plasma states, thereby enhancing data transmission rates and reliability in satellite uplinks and downlinks. Their capability to manipulate electromagnetic waves without mechanical movement, using principles of refraction and reflection, offers significant benefits such as beam steering and focusing, essential for optimizing signal coverage and minimizing interference in satellite communications. Recent research has showcased innovative applications of plasma antennas, including their use in reducing co-site interference through novel plasma shielding techniques and their potential for integration into Plasma Antenna Arrays (PAAs) for enhanced signal reception from GPS and Galileo satellites. Moreover, advancements in plasma antenna design, such as the development of smart plasma antennas with controllable plasma densities, underscore their adaptability and suitability for future satellite communication systems. Moving forward, continued research and development are essential to refine plasma antenna technologies, address practical challenges, and explore their full potential in next-generation satellite communication networks. This includes further investigation into plasma density management, scalability of plasma antenna arrays, and their integration into practical satellite systems to meet the increasing demands for higher data rates and reliability in global telecommunications. The evolution of plasma antennas holds promise for revolutionizing satellite communication technology, offering solutions that enhance performance, efficiency, and adaptability in a rapidly advancing space-based communication landscape.

Author Contributions

K.Alharbi and M.Alharbi wrote the review and both authors contributed to the final version of the manuscript.

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