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TOPICAL REVIEW

Plasma Antennas: A Comprehensive Review

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ABSTRACT This paper aims to comprehensively review the literature on Gaseous Plasma Antennas (GPAs). These innovative devices transmit electromagnetic (EM) signals through ionized gas, known as plasma, instead of conventional metal structures. GPAs offer distinct advantages over their metallic counterparts, particularly in performance reconfigurability. The paper begins by evaluating the EM properties of the plasma medium, exploring methodologies for its generation, measurement, and simulation. Subsequently, the prevalent GPA architectures are presented, distinguishing between active and passive concepts based on the plasma's primary role: either emitting EM signals or manipulating them. Additionally, unconventional GPA implementations, such as explosive or laser-based technologies, are examined. Finally, the paper assesses the most promising applications for leveraging GPAs in various fields.

INDEX TERMS Gaseous plasma antennas, plasma monopole, plasma dipole, plasma reflectarray, plasma transmittarray, plasma lens.

I. INTRODUCTION

It is possible to communicate an electromagnetic signal using plasma as a conducting medium rather than metal. This statement may strike some readers as peculiar or even elicit a skeptical chuckle. Hence, we are convinced that a review paper on plasma antennas is needed to shed light on the progress made in recent years and to delineate the necessary steps for the full development of this intriguing and sophisticated technology.

The generic term Gaseous Plasma Antenna (GPA) encompasses all devices that exploit an ionized gas, namely plasma, for telecommunication purposes [1]. Plasma is sometimes referred to as the fourth state of matter; it is a gas composed either partially or entirely of charged particles [2]. The concept of using a plasma discharge to transmit electromagnetic (EM) signals was first proposed in 1919 with the patent "Aerial Conductor for Wireless Signaling and Other Purposes" credited to J. Hettinger [3]. What is more attractive in this technology is its capability for extensive reconfiguration of plasma properties and, consequently, antenna performance [4]. Actually, it is possible to turn plasma on and off, allowing a GPA to electrically "disappear" when not in use [5]. Plasma is a dispersive medium whose EM response depends on both the signal frequency and material properties, such as density [6]. These properties can be manipulated by adjusting the electrical power to sustain the discharge [7]. As a result, GPAs offer remarkable advantages with respect to their metallic counterpart. A GPA can be reconfigured with respect to shape, frequency, and radiation pattern on millisecond time scales [8]. Thus, plasma is particularly appealing to realize antenna arrays that permit rapid beam steering at a lower cost than phased arrays [9]. Moreover, interference among

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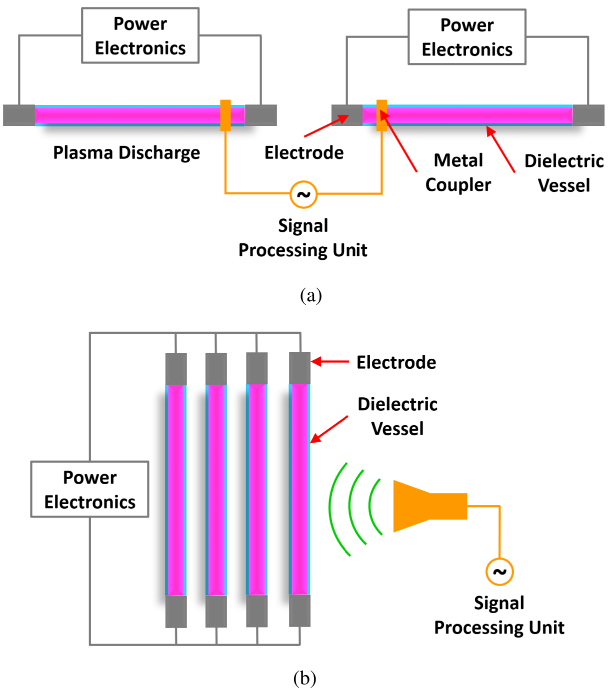

(a)

(b)

FIGURE 1. **Schematic of (a) active and (b) passive GPA concepts.**

plasma elements can be minimized by turning on only the GPAs that are actually transmitting and/or receiving [10]. The possibility of turning the main conductor into a neutral gas de-energizing the plasma discharge is the most unique property of GPAs. This enables stealth operations since the Radar Cross Section (RCS) of the antenna can be controlled [11]. Moreover, high-frequency antennas can transmit and receive through lower frequency GPAs [12]. Thus, it is possible to nest several devices, minimizing cost and interference [13].

So far, several concepts of GPAs have been proposed, mainly operating within the Radio Frequency (RF) spectrum, typically with frequencies below 30 GHz [3]. Some notable examples are half-wave dipoles [14], quarter-wave monopoles [15], Yagi-Uda antennas [16], reflectarrays [17], transmitarrays [18], and plasma lenses [19]. In spite of the huge variety of solutions available in the literature, almost all GPAs share the following components: (i) plasma discharge both confined within a dielectric vessel or in the atmosphere, (ii) a circuit dedicated to the ignition of the plasma (e.g., electrodes and power electronics), (iii) a signal processing unit. In the following, active and passive GPAs will be distinguished based on whether plasma elements are utilized to radiate the signal (referred to as active concepts, Fig. 1a) or to manipulate EM waves produced by a conventional antenna system (referred to as passive concepts, Fig. 1b). In active concepts, a metal coupler interfaces plasma with the signal processing unit [20].

The potentially disruptive features offered by GPAs have attracted the interest of research centers and industries. The applications that seem more suitable to exploit GPAs are protection from electronic warfare [4], satellite communications [21], and 5G/6G networks [22]. Actually, several companies have investigated GPAs for mobile phones, radio telescope arrays, and radar applications [23]. Noteworthy, GPAs have been proposed also for biomedical purposes [24]. Nonetheless, some issues have hindered the widespread diffusion of this technology. A non-negligible power budget shall be allocated to sustain the plasma discharge [25], GPAs usually under-perform metal antennas in terms of gain [26], and plasma technology is intrinsically complex [27], [28]. These problems can be reduced to the lack of plasma sources optimized for telecommunication uses. However, recent advances in terms of innovative plasma sources [29] and novel antenna concepts [30] gave a new impulse to the research on GPAs. To highlight just one indicator of this emerging trend, over the past five years, more than one hundred papers focusing on plasma antennas have been published.

The present work aims to review the literature on GPAs available nowadays and to outline possible developments in this technology. First, EM plasma properties are analyzed, presenting the main techniques to produce, measure, and simulate this peculiar medium (see Section II). The main active and passive concepts of GPAs are subsequently discussed in terms of theoretical, numerical, and experimental results (see Section III and Section IV). Finally, less common implementations and the most appealing application perspectives of GPAs are assessed (see Section V and Section VI). It is worth mentioning that this review is not intended for treating plasma metamaterials [31], antennas relying on solid-state plasma [32], and strategies to overcome the blackout that affects space vehicles re-entering atmosphere [33].

II. PLASMA MEDIUM

The EM response of the plasma medium is usually evaluated via the Drude model [34]. Given the standard operation frequencies (i.e., in the GHz range) and material properties [1], in GPAs, the relative plasma permittivity ε_p is formulated according to the cold plasma model neglecting ion's motion [6]. Namely, in the absence of any static magnetic induction field, ε_p reads [6]

$$\varepsilon_p = 1 - \frac{\omega_p^2}{\omega(\omega + \jmath\nu)}, \tag{1}$$

where ω is the angular frequency of the signal in rad/s, ω_p is the plasma frequency in rad/s, ν is the collision frequency in Hz, and $\jmath$ is the imaginary unit. The parameters ω_p and ν depend on macroscopic plasma parameters according to the following relations [6]:

$$\omega_p = \sqrt{\frac{q^2 n_e}{m\varepsilon_0}}, \qquad \nu = p_0 K(T_e), \tag{2}$$

where q is the elementary charge, m is the electron mass, ε_0 is the vacuum permittivity, n_e is the plasma density in m^{-3}, p_0 is

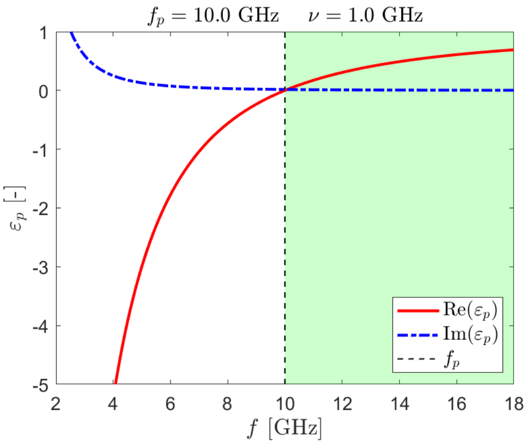

FIGURE 2. **Plasma dielectric permittivity vs. frequency. Plasma parameters: $n_e = 1.24 \times 10^{18}$ m^{-3}, $p_0 = 0.33$ mbar, $T_e = 3$ eV.**

the neutral gas pressure, and K is a rate constant that depends on the electron temperature T_e and the gas type [7]. Thus, ε_p depends on two reconfigurable parameters, namely ω_p and ν. The former can be controlled via the plasma density n_e which, in turn, is determined by the electric power to sustain the discharge [7]. The latter is driven by the gas type and pressure which can be controlled via a dedicated vacuum pumping system [7]. The parameters ω_p and ν affect also the plasma conductivity which reads [2]

$$\sigma_p = \frac{\varepsilon_0 \omega_p^2}{\nu - \jmath\omega} . \tag{3}$$

According to the Drude model, Eqs. 1, 3 describe both plasma and metals [35]. In metals, the density of free charges (i.e., electrons) is usually 10^{28} m^{-3}, namely $f_p = \omega_p/2\pi \approx 10^{15}$ Hz, and $\nu \approx 10^{14}$ Hz [35]. As a result, the condition $f \ll \nu \approx f_p$ holds for a RF signal (say $f \leq 30$ GHz). In this case, ε_p is almost imaginary and σ_p is real with values up to 10^7 S/m. Indeed, RF signals are dumped in short distances (from micrometers to millimeters) within metals due to Ohmic losses while propagation is possible on the surface of the conductors [35]. On the other hand, in GPAs $n_e \approx 10^{18}$ m^{-3} (i.e., $f_p \approx 10^{10}$ Hz) and $\nu \approx 10^9$ Hz being the neutral gas pressure in the millibar range. Namely, RF propagation in plasma is quite different than in metals being $\nu < f \approx f_p$. Specifically, if $f > f_p$ EM waves propagate within the plasma medium since Re(ε_p) > 0, otherwise only evanescent waves occur [12]. These two states are usually referred to as dielectric and conductive regimes; they are indicated with green and white background in Fig. 2, respectively. Moreover, in plasma, the conductivity is usually $\sigma_p < 100$ S/m. Being aware of the differences between the EM propagation in plasma and metals is key to designing GPAs properly and understanding their operation principles.

If plasma is produced in the presence of a static magnetic induction field $\boldsymbol{B}_0$, ε_p takes the form of an anisotropic dyadic tensor [34]. Notably, its expression depends on a third parameter called cyclotron frequency, ω_c, which reads [6]

$$\omega_c = \frac{qB_0}{m} . \tag{4}$$

The parameter ω_c can be reconfigured varying B_0 via electromagnets, namely solenoids whose current is controllable [7]. EM propagation in a magnetized plasma is quite complicated given the anisotropic nature of the medium: different wave modes, resonances, and cut-off frequencies can also be identified for propagation in free space [36]. The interested reader is referred to [6, Chap. 16] for further details.

Finally, it is worth mentioning that in some works on GPAs, more accurate formulations of ε_p have been assumed [37] based on the hypothesis of warm [38] and hot plasma [39], [40]. Nonetheless, major differences with respect to the cold plasma model have not been registered [26], [40].

A. PLASMA SOURCES

The plasma production sub-system is the most critical element of a GPA. In fact, it is in charge of generating a plasma that guarantees a suitable antenna performance, namely that satisfies the requirements imposed on ω_p and ν. These are expressed in terms of absolute values and spatial distributions, such as filaments, columns, or sheets [3]. Moreover, efficient plasma sources are mandatory to mitigate the major disadvantage of GPAs with respect to metal antennas, namely the power budget to generate plasma [1]. Plasma sources for GPAs shall rely on a simple design that aims at minimizing the amount and dimension of metal components (e.g., electrodes, wires, electronics, and eventual electromagnets), which might distort the radiation pattern [3]. Finally, the plasma production sub-system shall be designed to minimize the noise produced on the communication signal [14], [41] and the time required to switch on-off plasma (< 1 ms) [8].

The majority of GPAs envision a plasma discharge generated from a low-pressure gas (0.01–10 mbar range) and confined within a dielectric vessel [4]. Argon is the element most widely employed to generate plasma in GPAs [1]. Nonetheless several options have been explored in the literature, namely neon [42], krypton [26], xenon [31], air [43], helium [23], mercury vapor [44] and Penning mixtures [45]. The gas selection depends on practical factors such as cost (e.g., 10 k\$/kg for xenon) and the capability to realize custom discharges [46]. From a physical standpoint, heavier gasses (e.g., xenon) allow achieving larger ω_p at the expense of an increased collisionality ν [26].

Given the complexity of realizing a custom plasma source, the majority of GPAs are based on commercial fluorescence lamps [46]. In these devices, a glow discharge [7] is realized within a glass tube usually of cylindrical shape but also loop [4], U-shaped [47] and spiral [48] configurations are available. Plasma is generated by applying a potential difference in the range of hundreds of Volts [49] between a couple of electrodes placed at the opposite ends of the dielectric vessel. The gas pressure is in the millibar range,

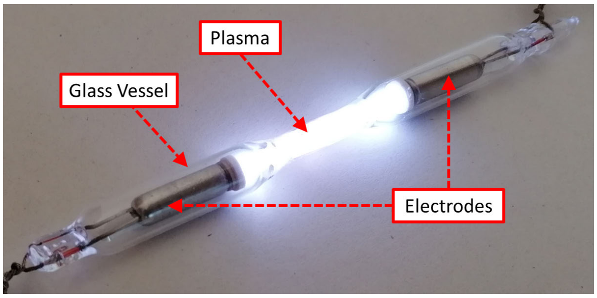

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FIGURE 3. (a) CCFL [10], and (b) surface wave [46] plasma sources.

and an almost uniform plasma density up to $n_e \approx 10^{18}$ m^{-3} can be achieved [50]. The power supplied to the plasma is provided in different ways. Namely, DC [19], pulsed DC [51], and AC ballasts operated in the kHz frequency range [52]. The selection of the power supply depends on factors such as efficiency, noise induced on the communication signal, and cost [5]. Improved performance (e.g., $n_e \approx 10^{19}$ m^{-3}) can be achieved by relying on custom Cold Cathode Fluorescent Lamps (CCFL) [21], see Fig. 3a. The latter is based on a similar concept of commercial fluorescent lamps and are usually driven with AC power supplies operated in the MHz range [14].

Commercial fluorescent lamps and CCFLs need wires connected to the electrodes at both ends of the plasma tube [1]. Thus, surface waves have been widely used to excite plasma from one end of the dielectric vessel, reducing the interference produced by metallic wires [15], see Fig. 3b. This solution is particularly appealing to implement monopole GPAs [5]. In contrast with CCFLs, the power to sustain plasma via surface waves is provided at a frequency close to or larger than the communication frequency, namely 430 MHz or 2.45 GHz (i.e., bands reserved for industrial and scientific purposes) [25]. Given the usual gas pressure in the millibar range, the plasma density is up to $n_e \approx 10^{19}$ m^{-3} and decreases of several orders of magnitude moving away from the wave source [53]. Surface waves are coupled to the plasma column via capacitive and inductive couplers [54] or relying on “surfaguides” connected to a magnetron [25]. The latter solution allows increasing the excitation frequency and managing power budgets up to hundreds of Watts.

Apart from the previously mentioned solutions, the literature is plenty of different types of plasma sources [27], [28]. Among them, it is worth mentioning Inductively Coupled Plasma (ICP) [55], [56], [57], hollow cathode-driven discharges [26], [58], [59], Capacitive Coupled Plasma (CCP) [60], [61], Helicon plasma sources [62], and microplasma discharges [63]. All these solutions, whose working principles can be delved into [7], have been exploited in the framework of GPAs. Generally speaking, they are more efficient plasma sources than glow or surface wave discharges [7]. Nonetheless, they are employed almost only for niche applications (e.g., reduction of RCS [64]), given the higher complexity and number/dimension of additional metallic components with respect to standard solutions.

Concepts that rely on plasma discharges generated in the atmosphere are available in the literature [65]. They usually rely on a pulsed laser beam to establish a low ionization path. Subsequently, a voltage difference of thousands of Volts is applied to achieve ionization up to 10^{25} m^{-3} [66], [67]. These systems are appealing given that a vacuum infrastructure is not needed, but the complexity of the electronics for plasma generation is their major disadvantage [3].

B. MEASURE OF PLASMA PARAMETERS

The design and optimization of GPAs heavily rely on the accurate characterization of the plasma density, electron temperature, and their spatial distribution. Precise measurement and control of these values are essential for designing efficient antennas [26]. So far, the experimental techniques most commonly employed are Langmuir probe measures, Optical Emission Spectroscopy (OES), and microwave interferometry [68].

Langmuir probes are diagnostic tools used to measure the plasma density and electron temperature directly. These probes include a small electrode immersed in the plasma, which collects current when biased with a voltage. By analyzing the current-voltage characteristics, one can deduce important parameters such as plasma density and electron temperature [69]. OES is a widely used technique for analyzing the composition and properties of plasma media by studying the light emitted from excited atoms and ions. Thus, the method provides valuable information on the energy levels and transitions within the plasma, allowing one to determine plasma density, electron temperature, and the elemental composition of the plasma [69]. Finally, microwave interferometry is a non-invasive technique used for the measurement of plasma density. The method operates based on the phase shift of microwave signals passing through the plasma. By comparing the phase difference between transmitted and reference signals, the plasma density along

TABLE 1. Comparison among plasma characterization techniques.

Method	Advantages	Disadvantages	Ease of Application
Langmuir Probes	Direct measurement of electron properties, high spatial resolution, localized measurements.	Intrusive, may perturb plasma, sensitivity to contamination, limited to low-pressure plasmas.	Highly adaptable to various configurations, relatively straightforward.
OES	Detailed composition and energy level information, non-invasive, real-time monitoring.	Limited to line-of-sight measurements, spectral overlap, requires calibration.	Suitable for homogeneous plasmas, challenging for complex structures.
Microwave Interferometry	Non-invasive, real-time measurements, high spatial resolution.	Requires calibration, sensitivity to noise, limited to low-density plasmas.	Versatile, suitable for inhomogeneous plasmas but requires a specialized setup.

the propagation path can be determined [69]. As a rule of thumbs, the uncertainty of Langmuir probe measures is in the order of 20–30%, it is about 10% for OES, and decreases below 10% relying on microwave interfermoetry [26]. The pros and cons of these three techniques are further elaborated in Table 1.

In the last decades, researchers have tried to adapt standard methods to address the specific needs of GPAs. Regarding microwave interferometry, the measured attenuation and phase drift of the propagating signal can be related to the real and imaginary part of ε_p and, in turn, to ω_p and ν. This technique has been presented in [70] assuming that the plasma is uniform and neglecting the reflections at the plasma-dielectric interface. In order to improve this methodology, the radial non-uniformity of plasma density is considered in [71]. This study also accounts for the reflections caused by the dielectric vessel. At the same time, in [72] an enhanced microwave interferometry method has been proposed. This approach involves inserting a plasma column into a waveguide through two holes and measuring the reflection coefficient. By correlating the plasma column's conductivity with the waveguide's input port reflection coefficient, the former parameter can be determined. With this approach a movable mechanism can be employed to vary the position of the waveguide along the plasma column for assessing the conductivity profile. A similar methodology is proposed in [73] where a waveguide cavity is loaded with the plasma column under test. Specifically, the plasma density is related to the value of the resonance frequency of the cavity. Alternative techniques to exploit microwave interferometry in the framework of GPAs are described in [74] and [75]. In the latter, a low-cost interferometric system that does not rely on a vector network analyzer has been developed.

Other approaches are available in the literature to measure plasma density. In [68] and [76] a technique is proposed to evaluate the plasma density distribution along a column excited via surface waves. Considering that the phase constant of a surface wave is a function of the plasma density, a pair of probes is used to measure the phase differences between two points. The measured phase difference is then used to determine the propagation constant and, consequently, the plasma density distribution along the column. In [77], the same research group has proposed another approach employing images of the excited plasma under test and relating the light emission to the plasma density's value.

C. NUMERICAL ESTIMATION OF PLASMA PARAMETERS

The biggest challenge in the design of a GPA is related to the prediction of realistic plasma properties via reliable numerical tools. In fact, plasma is an intrinsically complex medium whose simulation requires the simultaneous solution of Maxwell's, Navier-Stokes', and Boltzmann's equations [78]. Moreover, plasma is chemically reactive, the reaction and transport coefficients strongly depend on macroscopic quantities, and larger gradients than in usual gas dynamics are encountered [78]. Thus, for treating this problem with the computational resources available nowadays it is necessary to identify simplification hypotheses [78]. The picture is further complicated by the variety of solutions adopted to generate plasma since diverse hypotheses shall be formulated to handle the plasma produced in different sources [7].

In spite of these challenges, several numerical and analytical solutions have been successfully exploited to estimate plasma properties in GPAs. The GLOMAC code [79] has been used to simulate the plasma produced in commercial fluorescent lamps [80], [81], [82]. Mercury—noble gas discharges are solved by relying on the energy and diffusion equation of motion. Notably, the electron distribution function is not assumed Maxwellian but computed via a semi-empirical formulation. GLOMAC provides 1-dimensional (1D) radial profiles of plasma properties (e.g., the density of charged particles). The main advantage of this solver is the relatively short computational time (i.e., a few seconds) combined with quite accurate modeling of the plasma chemistry [79]. Custom CCFLs and hollow cathode-driven discharges have been studied with OpenFOAM routines derived from a software for space electric propulsion [49]. Cylindrical discharges operated via DC or AC ballasts can be simulated too. This code solves the diffusion equation, providing a 1D axial profile of the plasma properties. The computational time is limited to a few minutes, and flexibility is offered in terms of discharge dimensions, working gas, and power feeding [49]. Custom glow discharges have also been simulated with the commercial solver COMSOL® [83]. Notably, the plasma diffusion can be resolved in a 2-dimensional (2D) radial-axial domain.

In the case of plasma sources driven by surface waves, other approaches have been adopted. In fact, the simulations are more complicated than in glow discharges given that the plasma dynamics is intrinsically related to the wave propagation. Specifically, Maxwell and Navier-Stokes/Boltzmann equations shall be solved self-consistently [78]. To avoid excessive complexity, a semi-empirical model has been proposed to obtain a quick estimation of the plasma parameters along the axis of a discharge sustained by surface waves [15]. A much more refined approach has been proposed in [39] and [84] where Maxwell's equations are coupled to the plasma's diffusion equation of motion. The most interesting aspect of this code is that the EM propagation is modeled very accurately, given that the hot plasma hypothesis is enforced. A similar approach is proposed in [53] and [85]; notably, in [85], the cold and hot plasma hypotheses are compared, showing no major differences. Surface wave-driven discharges have been simulated adopting also the Particle-In-Cell approach [86]. This is a very accurate technique in which plasma is modeled as an ensemble of computational particles. As a result, no hypotheses on the particle distribution function are required, but the computational burden can be huge [78]. A similar approach has been adopted to study microplasma discharges too [87].

Finally, a self-consistent model to predict the plasma properties in an ICP plasma discharge for RCS reduction is presented in [55]. The plasma diffusion is solved in a 2D radial-axial domain with the commercial software COMSOL®. Concurrently, the 13.56 MHz signal that energizes the plasma is evaluated with the same routine.

III. ACTIVE CONCEPTS

The definition of "active" GPAs includes all the designs in which plasma elements are necessary to generate the radiation and not only to reflect/scatter a signal produced by another conventional antenna. In these designs, a signal coupler [88] is usually needed to interface the "active" plasma elements with the signal processing unit. Examples of active GPAs are half-wave dipoles [14], quarter-wave monopoles [15], and Yagi-Uda antennas [16].

A. ANALYTICAL MODELLING

Analytical models are available to preliminary estimate the performance of active GPAs as half-wave dipoles [34] and quarter-wave monopoles [85]. In analogy with metallic devices, radiation properties can be evaluated once the electric currents induced on the antenna's conductors are known [89]. Nonetheless, EM propagation in a plasma column is different from a metal rod [35]. For the sake of simplicity, it is assumed that a cylindrical plasma column behaves as an open waveguide that sustains surface-wave propagation [90]. Enforcing this hypothesis, several authors [34], [85], [91] have proposed a dispersion relation to compute the axial propagation constant β given a fixed working frequency f, radius of the plasma column a, and plasma relative permittivity ε_p (see Eq 1):

$$\frac{\varepsilon_p I_1(\tau_p a)}{\tau_p I_0(\tau_p a)} + \frac{K_1(\tau_0 a)}{\tau_0 K_0(\tau_0 a)} = 0 \,. \tag{5}$$

The symbols I_0, I_1, K_0, and K_1 indicate the modified Bessel's functions of the first and second kind. The parameters $\tau_p = \left(\beta^2 - \varepsilon_p k_0^2\right)^{1/2}$ and $\tau_0 = \left(\beta^2 - k_0^2\right)^{1/2}$ represent the transverse propagation constant in plasma and air, respectively, where $k_0 = 2\pi c_0/f$ is the wavenumber and c_0 the speed of light in vacuum. The coefficient $\beta = 2\pi/\lambda_{\text{eff}}$ gives the effective wavelength λ_{eff} which is the reference quantity to determine the length of a half-wave dipole or quarter-wave monopole [92]. Eq. 5 relies on several hypotheses such as propagation of TM modes, absence of a dielectric vessel between plasma and air, and uniform plasma. A dispersion relation that accounts for generic wave modes is reported in [90] and [93], the presence of a dielectric that confines plasma is accounted in [94] and [95], and non-uniform plasma is assumed in [96] and [97]. Notably, once λ_{eff} and the length of the active GPA are known, the radiation pattern can be estimated relying on the thin wire approximation [94], [98] or integrating the currents' contribution in the plasma volume [90], [99]. Analytical models provide reasonable agreement with experiments [95], [100] and represent a powerful tool to predict general performance trends. For example, the resonance length of a GPA is smaller than in an equivalent metallic system [34], [95]. The propagation of surface waves on a plasma column is broadly reviewed in [101].

B. PLASMA MONOPOLES AND DIPOLES

Over the past two decades, researchers demonstrated the potentiality of active GPAs both as transmitters and receivers across a broad frequency spectrum, ranging from approximately 1 MHz to several GHz [5], [102]. Monopoles and dipoles are the most common forms of active GPAs thanks to their tunability in terms of operation frequency and radiation pattern [15], [103], [104]. Additionally, they possess the ability to function as on/off switchable antennas, offering distinct advantages for various array structures and steering configurations [57], [105], [106].

Plasma monopoles and dipoles require a relatively high degree of ionization to operate properly. Specifically, the condition $\omega < \omega_p$ shall hold to enable the signal to propagate as a surface wave, similarly to what happens in conventional metal antennas [1], [5], [15]. Various excitation methods, including DC or AC ballasts, CCFL, and surface waves, can be used for igniting plasma. DC or AC ballasts and CCFL solutions involve applying a voltage between a pair of electrodes that are mounted at both ends of the dielectric vessel, confining the plasma [14], [21], [82]. In contrast,

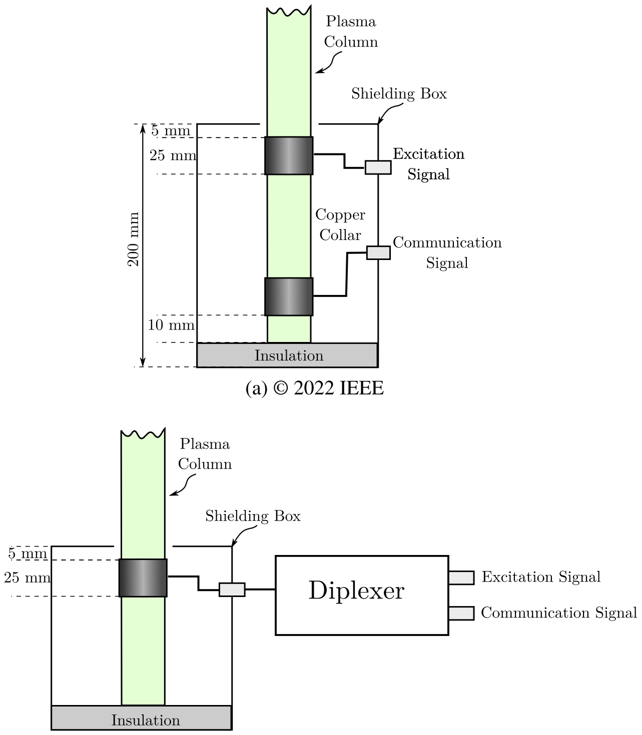

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FIGURE 4. **(a) Conventional and (b) improved structures for applying excitation and communication signals to a surface wave-driven GPA [95].**

in the surface wave method, the plasma is excited only from one end of the column. The latter excitation method emerges as the most commonly employed for active GPAs due to its superior tunability and stealth [23], [39], [107] even at the expense of a higher complexity [14].

Once the plasma is ignited, the communication signal has to be coupled to the antenna. Regardless of the excitation type, various methods can be utilized to apply communication signals to active GPAs, including coupling structures [46], [88], [108] and direct connection to the ionized gas using a conductive pin or electrode [14], [109], [110]. Coupling structures, either capacitive or inductive, are the most commonly used [111]. Specifically, inductive coupling based on multi-turn coils has been employed in some studies [57] even though the most diffused solution is the capacitive one [112]. At the same time, using a pin at the bottom of the column for applying the signal has been reported as a low-cost, simple, and relatively efficient alternative [14], [109], [110]. An example is illustrated in Fig. 4. The more standard implementation (see Fig. 4a) involves two wave ports: one for feeding the excitation signal and another for injecting the communication signal [39], [107], [113]. This implementation minimizes the coupling effects between the excitation and communication signals if the separation between the two ports is sufficiently large [72]. However, considering that the maximum plasma density (and consequently conductivity) occurs at the location of the excitation port, increasing the gap between the two ports results in higher losses and lower radiation efficiency [84], [97]. Thus, some studies have improved wideband matching and conductivity by employing a single coupler for both excitation and communication signals (see Fig. 4b). To achieve this, a passive microwave component, such as a diplexer, a directional coupler, or a filter, is used before the coupling sleeve [14], [95], [114]. This ensures signals are fed from the point of maximum plasma density, thereby enhancing antenna efficiency.

1) EFFECT OF PLASMA PARAMETERS

Several theoretical, numerical, and experimental investigations have been conducted to assess the radiation characteristics of plasma monopoles and dipoles. Numerical and experimental analyses underscore the ability to enhance the performance of GPAs by manipulating their functionality through the adjustment of parameters such as excitation power [53], [97], [120], excitation frequency [25], [76], and gas pressure [42], [81], [82]. These parameters can be used for the dynamic tuning of the operation frequency, bandwidth, and gain of the antenna.

The radiation efficiency, bandwidth, and resonant length of active GPAs differ from those of conventional metallic antennas [109], [121]. For instance, the efficiency of a surface-wave driven plasma monopole may dip below 50% [5] or even below 40% [76]. This is because the plasma density, and consequently the plasma conductivity, linearly decreases from its maximum at the excitation port to a critical value at the end of the ionized section of the column. At the excitation port, the plasma density is proportional to the excitation power [107], while the plasma density distribution is a function of the excitation frequency [25] and the permittivity of the tube material [122]. Therefore, it can be concluded that improving the radiation efficiency of a GPA may be achieved by: 1) increasing the excitation power, which in turn enhances the average plasma density in the column [46], 2) optimizing the excitation frequency that affects the plasma density at the end of the plasma column, and 3) by selecting an appropriate material for the dielectric vessel.

Notably, the dependence of antenna performance on plasma density in DC, AC, and CCFL discharges is similar to surface-wave implementations [53]. For example, increasing the plasma density in a DC-excited plasma column, which can be achieved by increasing the excitation voltage, enhances the plasma conductivity and consequently improves the antenna efficiency [123]. This, in turn, alters impedance matching and the resonant frequency of the antenna [103]. Similarly, the radiation pattern is another characteristic that can be significantly influenced by plasma parameters, thus offering greater flexibility compared to metal antennas [123]. In fact, when the plasma frequency significantly surpasses the operation frequency, and the collision frequency is sufficiently low, the radiation pattern of a plasma antenna is very close to its metallic counterpart (i.e., less than 1 dB difference) [26].

Gas type and its pressure also significantly impact the radiation characteristics of GPAs by influencing complex permittivity and collision frequency [42]. For instance, comparing antennas based on pure argon, pure neon, and a combination of these gases with mercury shows that pure argon gas offers the highest gain, while a mixture of argon gas and mercury results in higher losses and consequently lower antenna gain [42]. Conversely, pure neon gas, due to its lower degree of ionization, yields lower density compared to a mixture of neon gas and mercury at a fixed excitation power [117]. It should be noted that increasing gas pressure in a fixed-length antenna results in higher collision frequency and plasma density [76]. Although higher plasma density improves the efficiency, the predominant effect of increased collision frequency reduces the antenna efficiency [76]. So, lower collision frequencies are preferred for efficient GPAs [42], [82], [107]. It is noteworthy that the resonant frequency and input impedance of the antenna are minimally affected by collision frequency [103].

The geometric dimensions of the antenna, including its radius and length, are fundamental parameters that should be carefully selected. The impact of radius and length on the radiation characteristics is extensively discussed in the literatures [76], [105], and [124]. Research by [124] indicates that GPAs with smaller radii demonstrate improved return loss and overall antenna characteristics compared to their larger counterparts. Similar to traditional monopole antennas, the resonant length of a plasma antenna increases as its radius decreases [104]. However, it is important to note that a larger radius may lead to non-uniform radial density in the plasma column, affecting radiation characteristics [125]. Typically, a zero-order Bessel function is considered for radial density distribution [97].

Finally, numerical investigations show that the radiation characteristics of an active GPA may be changed by applying an external magnetic induction field [34]. The radiation efficiency can be manipulated by adjusting the magneto-static field, particularly at low plasma densities values. Moreover, this study shows that the shape of the radiation pattern remains almost insensitive to the applied magnetics induction field.

2) ANTENNA TYPES

Various geometries and configurations have been proposed to implement plasma monopoles and dipoles. Specifically, in addition to cylindrical solutions [14], [15], several other configurations have been proposed in the literature, including U-shaped [116], folded dipole [20], and cross dipole [21], [57] antennas. Notably, compared to conventional monopole plasma antennas, a U-shaped GPA benefits from a smaller size and an easier connection to a DC or AC power supply [102], [116].

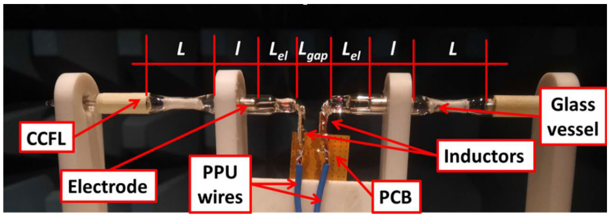

FIGURE 5. **A plasma dipole under test [14] © 2021 IEEE.**

Even though the most widely diffused active GPA is the monopole, several studies focused on dipole configurations [14], [111]. Dipole plasma antennas have been numerically studied in [49] while their implementation based on custom CCFLs has been discussed in [14] (see Fig. 5). The radiation efficiency and gain of this antenna have been reported to be 25% and −4.2 dBi, respectively. Moreover, electromagnetic analysis of folded-dipole configurations using the FDTD method demonstrated a wide-band reconfigurability (81% bandwidth) [20]. In this investigation, the effects of the geometrical dimensions and plasma frequencies on the antenna performance are also presented. A numerical analysis on a crossed dipole GPA for GNSS has been presented in [21], demonstrating promise for circular polarization in the L band. An improved version of this concept has been implemented in [57] which is capable of linear and circular polarization and whose efficiency is about 30–50%.

Arrays of active GPAs offer beamforming and reconfigurability capabilities, enhancing radiation characteristics by switching plasma columns on and off. Among pioneering investigations [5], a simple beamforming array is experimentally proved using two plasma monopoles. Subsequent numerical studies explore the effects of physical properties and dimensions of plasma elements in linear [105], planar [106], and nonplanar [126] array configurations, aiming at improving antenna radiation characteristics. Notably, significant enhancements in gain and pattern of GPAs are achieved by selectively activating plasma elements [57], [106]. Active GPAs with miniaturized dimensions are another topic, which is especially important in antenna arrays [102], [127]. For example, [127] suggests a miniaturized antenna with a 16 mm plasma element for 2.45 GHz applications, while [102] proposes a C-band monopole with a peak gain of −0.6 dBi.

To sum up, under specific conditions, namely when the plasma frequency significantly exceeds the signal frequency and collision frequency, the radiation characteristics of active GPAs can closely match those of conventional metallic antennas [35]. However, under typical discharge conditions, the performance of a GPA is lower than that of its metallic counterpart. Constraints, including noise [5], [15] and nonlinearity [128], are other issues in active GPAs. Concerning the noise issue, plasma discharges excited via DC or AC ballasts produce spurious signals up to microwave frequencies [5]. On the other hand, utilizing surface wave excitation can reduce noise at the cost of increased excitation power [15]. Concerning the nonlinearity, GPAs exhibit a

TABLE 2. Active GPA implementations.

Excitation method	**Reference**	**Gain [dBi]**	**Efficiency [%]**	p_0 **[mbar]**	ν **[GHz]**	$\lvert S_{11}\rvert$ **[dB]**	f **[MHz]**	n_e **[m^{-3}]**	**Prototype**
DC	[115]	< -5	n.a.	2.67-13.33	n.a.	< -10	269 - 287 (6.47%)	$\approx 10^{18}$	YES
	[102]	-0.6	28.8%	2.6	10	< -6	-	2.65×10^{19}	YES
AC [kHz]	[116]	< -10	n.a.	5	6	0	183 - 500 (93%)	10^{17}	YES
	[29]	-1.3 - 0.17	n.a.	1-6	3	< -10	150 - 225 (40%)	3.2×10^{17}	YES
	[117]	n.a.	40-50%	< 6	7-8	< -15	170 - 300 (55%)	5.46×10^{17}	YES
	[57]	< -2	30-50%	1	1	< -10	200 - 320 (46%)	10^{17}	YES
CCFL [MHz]	[110]	-2.97	20%	2.6	1.69	< -15	-	3.3×10^{18}	YES
	[14]	-4.2	$\approx$ 25%	2	6	< -10	-	3.5×10^{18}	YES
Surface Wave	[118]	-	$\approx$ 50%	1.3	1-2	n.a.	-	4×10^{17}	YES
	[5]	n.a.	25%	1.3	0.5	n.a.	-	$\approx 5 \times 10^{17}$	YES
	[53]	< -2.5	n.a.	1.3	1.5	n.a.	-	8.4×10^{18}	YES
	[107]	< -5	n.a.	0.25 - 0.6	0.3-0.6	< -10	110 - 300 (92%)	0.92×10^{18}	YES
	[119]	-8 (simulated)	n.a.	0.5	0.5	< -20	150 - 250 (50%)	$\approx 5.89 \times 10^{17}$	YES
	[46]	< -4	n.a.	0.4	0.2	< -15	400 - 480 (18%)	4×10^{17}	YES
	[109]	-1 (simulated)	56% (simulated)	6	8	< -10	145 - 250 (53%)	$> 10^{19}$	YES
	[76]	n.a.	15%	0.2	0.8	< -10	-	4.5×10^{17}	YES
	[95]	n.a.	n.a.	0.1	n.a.	< -7	301 - 720 (82%)	10^{16}	YES

TABLE 3. Categorization of different excitation techniques via qualitative indicators specific for the GPA application.

Excitation method	**Implementation complexity**	**Tuning flexibility**	**Stealth**	**Controllable plasma frequency**	**Efficiency**	**Gain**
DC	Medium	Low	Medium	Medium	Medium	Medium
AC [kHz]	Low	-	Medium	Low	Medium	Medium
CCFL [MHz]	Medium	High	Medium	High	High	High
Surface Wave	High	High	High	High	High	Medium

Radiation efficiency: below 20%: Low; between 20% and 40%: Medium; over 40%: High.
Tuning flexibility: below 25%: Low; between 25% and 50%: Medium; over 50%: High.
Gain: below -5 dB: Low; between -5 dB and 0 dB: Medium; over 0 dB: High.
Stealth: one end excitation: High; two end excitation: Medium.

more pronounced power content in harmonics compared to metallic antennas [128]. Nevertheless, active GPAs still offer sufficient performance for wireless communication and possess unique properties not found in metal antennas in terms of reconfigurability [53]. Finally, based on the state-of-the-art experimental literature reviewed, different active GPAs are compared in Table 2. Processing this information, the pros and cons of various implementations are summarized in Table 3.

C. YAGI-UDA ANTENNAS

An overview of the research on Yagi-Uda plasma antennas is presented in the following, focusing on reconfigurability, beamforming, hybrid designs, simulation techniques, and practical implementations. In [130], the authors introduce an electronically controlled plasma reflector antenna array with pattern reconfigurability based on the Yagi-Uda technology. The use of plasma as a dispersive material in the array enhances its performance, offering stealth capabilities when the plasma columns are off. Adopting equal amplitude and phase control on the plasma discharges simplifies pattern reconfigurability implementation. In [13], combining the plasma antenna and the Yagi-Uda concepts, the design of a structure with reconfigurability, narrow beam, and high gain (up to 9.5 dBi) is presented. The paper includes simulation and experimental results that validate the performance of the array at 1.2 GHz. The study also explores plasma absorption of electromagnetic waves and its potential applications in stealth technology. The design and analysis of a plasma Yagi-Uda antenna are addressed in [129], demonstrating good directivity and high gain. The study compares the performance of the plasma implementation with that of metal antennas, highlighting advantages such as stealth, reconfigurability, and low mutual coupling. The experimental results show consistency between simulation and measurement, with the Yagi-Uda plasma antenna achieving a gain of up to 9.4 dBi. In [131] the authors propose a reconfigurable surface wave-driven Yagi-Uda monopole array. By varying the excitation power of plasma monopoles, the resonant frequency can be adjusted in the range of 40–120 MHz, maintaining consistent gain and directivity. The study provides insight into the design and optimization of plasma-monopole arrays, emphasizing the impact of excitation power on the array efficiency. A fair comparison between conventional (metallic) and Yagi-Uda plasma antennas can be found in [16], with a special emphasis on miniaturization and reduced weight. The study explores the use of Yagi-Uda plasma antennas in base stations for ship routing, highlighting the potential for adjusting plasma parameters to enhance miniaturization. Practical implementations include the use of this technology in the framework of smart antennas with impedance-matching capabilities (see Fig. 6). Regarding the use of a Yagi-Uda antenna as a highly directive radiator, an end-fire plasma array antenna (E-PAA) is introduced in [61]. This paper presents a comparison between the E-PAA and a conventional plasma circular reflectarray. The E-PAA outperforms the reflectarray in terms of direction pattern, gain, RCS reduction, and activating power. The study suggests potential applications in stealth and high-level

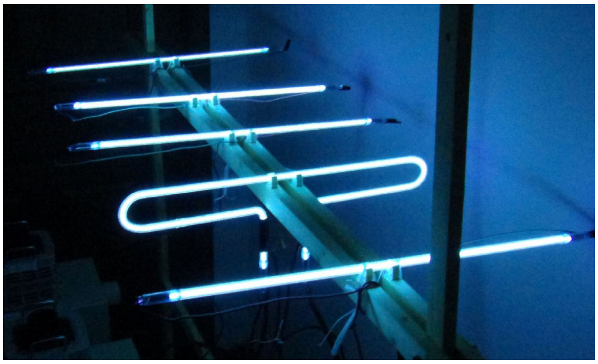

FIGURE 6. **Yagi-Uda plasma antenna [129] © 2013 IEEE.**

integration of radio transceivers for wireless communications. The practical viability of the E-PAA is supported by measured results of gain and efficiency, up to about 5.3 dBi and 60%, respectively. Finally, hybrid configurations in which both metallic parts and plasma discharges are finely tuned to work together are also present in the literature. The paper [132] presents a hybrid metal-plasma Yagi-Uda antenna operating at 1.55 GHz. The study addresses challenges in achieving reconfigurability in realistic systems, emphasizing the influence of dielectric vessels, metallic electrodes, and collision frequency on radiation patterns. The latter work includes a feasibility study of a detailed and realistic model, showcasing the potential to achieve reconfigurability through proper antenna design.

D. OTHER DESIGNS

Monopole, dipole, and Yagi-Uda plasma antennas represent innovative approaches to antenna design, harnessing the unique properties of plasma to achieve enhanced performance, flexibility, and adaptability in wireless networks. However, different kinds of active GPAs have been recently proposed. A brief overview of these platforms is presented by including inverted F, curl, helix, leaky wave antennas, nested monopoles, magneto-electric dipoles, and microstrip antennas. First, an inverted F plasma antenna offers reconfigurability through the control of plasma properties, such as density. Specifically, the antenna's resonant frequency and radiation pattern can be adjusted dynamically in the range 150–270 MHz [41], [119]. Due to their lightweight and easy integration, these GPAs may find applications in vehicular systems and tracking devices (see Fig. 7). Instead, in [21] a curl plasma antenna is proposed as a building block in the Global Navigation Satellite System (GNSS). Indeed, the antenna can work in the L-frequency band while achieving circular polarization (CP). Differently, in [133], a circularly polarized curl antenna is designed for portable Radio Frequency Identification (RFID) reader with CP behavior with a maximum gain of 8.1 dBi and 3 dB axial ratio at 160 MHz. Recently, it has been demonstrated that wide-band CP emission can also be efficiently achieved by considering helical antennas (HA). In [134], the authors demonstrate a plasma HA in which the dimensions are optimized for CP end-fire radiation in the frequency band of 6–12 GHz. The CP bandwidth is controlled by changing the number of plasma helix turns. The helix shape is also considered in [135] where the radiation is generated through the interaction of electromagnetic waves with the helical plasma column, inducing a helical current along the structure. This current, in turn, produces radiation in a manner analogous to a conventional helical antenna. Similarly, leaky wave plasma antennas utilize the phenomenon of wave leakage in plasma to generate and control electromagnetic patterns. By modulating the properties of the plasma medium, such as its density or electron temperature, the direction and characteristics of the radiated wave can be adjusted [136], [137], and [138]. In particular, the use of plasma as a tunable material to achieve beam scanning by varying the plasma density is proposed in [136], [137]. Notably a planar leaky-wave antenna is proposed for MIMO applications in [138]. Moreover, the necessity to further increase the communication capabilities over ultra-high frequency (UHF) and super-high frequency (SHF) bands has pushed the design of the so-called nested plasma antennas. Typically, in these platforms, a conventional GPA is surrounded by a commercial plasma tube in order to provide a great amount of flexibility in terms of tunability and controllability [139], [140]. It is worth mentioning that magneto-electric (ME) plasma antennas have also been recently proposed. Magneto-electric antennas consist of an electric dipole and magnetic dipole proximity coupled using a single feed. They are proposed for application in mobile base stations and in ultra-wideband systems. In this context, different array layouts based on ME plasma antennas with wide-band CP behavior are analyzed in [141] and [142]. Moreover, plasma micro-strip antennas can be efficiently implemented for mobile base stations in 5G wireless networks [22]. Microplasma discharges have been assessed for reconfigurability in microstrip antennas thanks to their moderate power consumption, in the range of 1 W [63]. As a closing remark, it is worth mentioning that among these appealing concepts, only the inverted F plasma antenna has been demonstrated experimentally [41], [119].

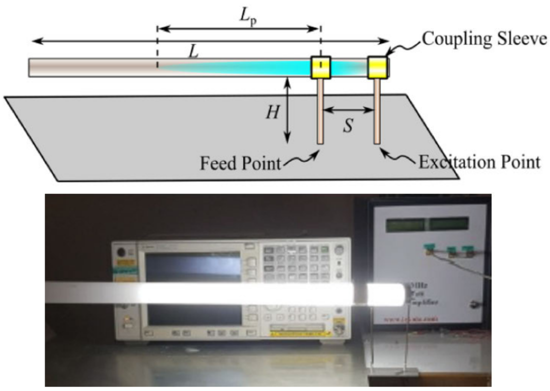

FIGURE 7. **Inverted F plasma antenna [41], [119] © 2019 IEEE.**

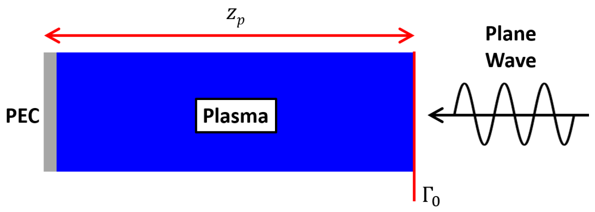

FIGURE 8. Schematic of the plasma slab analyzed with the theoretical model [12].

IV. PASSIVE CONCEPTS

The definition of "passive" GPAs includes the concepts in which plasma elements are employed to reflect, scatter, or focus EM waves. Namely, the radiation is produced via a conventional antenna, and thus, plasma discharges do not interface directly with the signal processing unit. Examples of passive GPAs are reflectarrays [17], transmitarrays [18], and plasma lenses [19].

A. ANALYTICAL MODELLING

EM waves propagating in air that impinge plasma undergo a certain reflection due to the discontinuity between the two media [143]. At the same time, waves in plasma and air present different wavelengths and, in turn, different phases [6]. The simplest way to quantify these effects is by investigating the dynamics of an infinite plasma slab (see Fig 8) [12]. Specifically, a plane wave is assumed to impinge normally a uniform slab of thickness z_p. According to the formalism of the ABCD matrices [143], a plasma slab can be characterized via the following coefficients

$$A = \cos\left(2\pi\sqrt{\varepsilon_p}\frac{z_p}{\lambda_0}\right), \tag{6a}$$

$$B = -j\frac{Z_0}{\sqrt{\varepsilon_p}}\sin\left(2\pi\sqrt{\varepsilon_p}\frac{z_p}{\lambda_0}\right), \tag{6b}$$

$$C = -j\frac{\sqrt{\varepsilon_p}}{Z_0}\sin\left(2\pi\sqrt{\varepsilon_p}\frac{z_p}{\lambda_0}\right), \tag{6c}$$

$$D = \cos\left(2\pi\sqrt{\varepsilon_p}\frac{z_p}{\lambda_0}\right), \tag{6d}$$

where λ_0 is the wavelength in air, Z_0 the intrinsic impedance of vacuum, and ε_p the plasma relative permittivity (see Eq 1). To preliminary assess the performance of a transmitarray, air is assumed at both sides of the plasma slab [144]. Consistently, the reflected and transmitted fields are estimated via the complex transmission (T) and reflection (Γ) coefficients

$$T = \frac{2}{A + B/Z_0 + CZ_0 + D}, \tag{7a}$$

$$\Gamma = \frac{A + B/Z_0 - CZ_0 - D}{A + B/Z_0 + CZ_0 + D}. \tag{7b}$$

On the other hand, to study a reflectarray, a layer of Perfect Electric Conductor (PEC) is assumed on one side of the plasma slab [144]. As a result, the reflection coefficient Γ_0 reads

$$\Gamma_0 = \Gamma - \frac{T^2}{1+\Gamma}, \tag{8}$$

where T and Γ are computed according to Eq. 7. Other models have been proposed to generalize the present formulation. A methodology to evaluate the behavior of a magnetized plasma is discussed in [36], the presence of a dielectric layer between plasma and air is accounted for in [38], and the effect produced by plasma inhomogeneity is evaluated in [145]. Notably, the main advantage of this approach is its relative simplicity, which allows for the identification of the parameters that have a major impact on a passive GPA. The EM response and the possibility of reconfiguring the performance are driven by the thickness of the plasma elements with respect to the wavelength (z_p/λ_0) and the plasma properties (ε_p) [12].

More refined analytical models have been proposed to study passive GPAs that rely on cylindrical plasma elements [51], [146], [147]. For reciprocity, when a plane wave impinges a cylindrical plasma column the EM field scattered can be described via a surface wave [90] (see Section III-A). Thus, it is possible to estimate the far-field radiation by summing the contributions provided by each element that constitutes the array. This approach is quite powerful since it allows the synthesis of the relative position of the plasma scatterers [51]. The methodology has been generalized in [148] to evaluate the field scattered by a dielectric rod surrounded by a plasma with an elliptical cross-section.

B. REFLECTARRAYS

One of the first attempts to exploit GPAs consists of using plasma elements as planar reflectors [43], [58], [164]. The same approach was effectively exploited by applying a microwave lens on top of a plasma discharge chamber [152], [165]. Interestingly, these works contributed to the definition of the building blocks for more complex antennas, namely reflectarrays capable of achieving tunable beam shaping and steering. Following this path, researchers [150], [151] proposed squared arrangements of plasma fluorescent tubes as reflectarrays fed by either a metal monopole or dipole at the center of the square. Both these solutions provided beam-forming and beam-steering by selectively switching the plasma tubes on and off. In particular, in [151] a numerical investigation is presented yet comprehending the use of an external magnetic field for additional gain tuning. In contrast, a full working prototype is presented in [150] which includes 8-multibeam and omnidirectional antennas. This approach, however, shows limited switching time (≈ 60 ms) due to the large tube's thermal time constant. Moreover, the lamp's frequent switching hampers its lifespan. Nevertheless, this solution remains cost-effective for realizing reconfigurable antennas, as fluorescent lamps are less expensive than electronic components used in conventional reflectarrays, like switches and phase shifters. The same concept is applied

TABLE 4. Plasma-based reflectarray implementations.

Reference	RF Source	Gain [dBi]	$\lvert S_{11} \rvert$ [dB]	p_0 [mbar]	ν [GHz]	n_e [m^{-3}]	Steering Range	f [GHz]	Prototype
[58]	horn	n.a.	n.a.	0.133-0.533	0.01	1.4×10^{18}	0°–360°	10.5	YES
[43]	Cutler feed antenna	n.a.	n.a.	0.133-0.666	n.a.	12×10^{17}	0°–360°	10	YES
[149]	horn	19.56-21.45	n.a.	n.a	7	n.a	0°,30°,30°	12	NO
[18]	horn	12.6	n.a.	n.a.	7	n.a.	10°–70°	12	NO
[47]	$\lambda/4$-dipole	5.7-10.8	$\approx$ -15	19×10^{-3}	0.9	6.13×10^{17}	n.a.	2.4	YES
[17]	$\lambda/4$-dipole	9	-10	n.a.	0.9	6.13×10^{17}	0°-48°-360°	2.4	YES
[150]	$\lambda/4$-monopole	8.2-9.3	n.a.	n.a.	n.a.	n.a.	0°-45°-360°	0.75	NO
[151]	$\lambda/2$-dipole	n.a.	n.a.	19×10^{-3}	0.01	1×10^{18}	0°-90°-360°	2.27	NO
[80]	monopole	n.a.	-29.05	n.a.	n.a.	1.13×10^{18}	0°-30°-360°	2.4	YES
[152]	horn	25-26	n.a.	n.a.	n.a.	1×10^{18}	0°	9.5	YES
[9]	$\lambda/2$-dipole	5	-9.2	2	n.a.	4×10^{18}	0°-15°-360°	1.45	YES
[153]	helical antenna	9.21	n.a.	n.a.	0.4	n.a.	37°-50°	0.927	YES
[154]	helical antenna	9.21	n.a.	pres	0.4	n.a.	37°-50°	0.927	YES
[155]	helical antenna	11.07	n.a.	n.a.	0.4	n.a.	80°-100°	0.927	YES
[156]	monopole	n.a.	n.a.	n.a.	4.6	2.6×10^{17}	0°–360°	1.35-1.55	YES
[157]	horn	18.4-19.8	n.a.	n.a.	9	3.14×10^{18}	10°-20°-30°-40°	12	NO
[158]	horn		$\approx$ -8	n.a.	2	5.1×10^{18}	±10°,±32°	7-11	NO
[159]	short linear antenna	n.a.	n.a.	4	n.a.	$0.7 - 1 - 2 - 4 \times 10^{17}$	n.a.	0.5-1.5	YES
[160]	n.a.	n.a.	n.a.	2	1.6	5×10^{22}	30°	10	NO
[161]	n.a.	n.a.	n.a.	0.4	0.31	8×10^{18}	±29°	10	NO
[162]	n.a.	n.a.	n.a.	4	0.31	$4.9 \div 13.7 \times 10^{17}$	0°-30°	10	NO
[163]	n.a.	n.a.	n.a.	n.a.	1.57	11.3×10^{18}	±30°	12.5, 27.5	NO

in [17] that implemented a reconfigurable reflector made from a circular arrangement of 15 commercial U-shaped plasma tubes surrounding a central monopole. The selective switch of the plasma discharges enables beam-shaping capabilities. The prototype showed a gain of 9 dBi and offered an operation bandwidth of 46% around 2.4 GHz. The authors claimed this to be the first example of implementing an actual working device, showing a good match with simulation and appealing performance, both on gain and cross-polarization rejection. Moreover, they confirmed that the dielectric vessel used to enclose plasma does not impact the quarter wave antenna radiation pattern [47]. Some years later, this approach has been further explored in [9] by proposing a plasma reflector antenna, working on the Galileo navigation frequency band (i.e., $\approx$ 1.45 GHz), and capable of electronically reconfiguring the radiation pattern. The antenna featured a central metallic half-wavelength dipole surrounded by a planar circular array of 36 custom-made cylindrical plasma discharges. The device, shown in Fig. 9, is still at a lab stage of development but constitutes a quite mature example of a real antenna, and an extensive characterization of the plasma density by microwave interferometry also supported the results. Further, the device showcased notable switching time within μs scale. More recently, other authors [8], [156], [159] rediscovered the same concept with very similar vessel arrangement and relying on parameters, such as working frequency, driving current, and plasma configurations, to tune and control the radiation pattern, achieving switching time of 0.6 ms [156].

Interestingly, plasma reflectarrays have been implemented with different feeding antennas, such as helical [153]. An arrangement of 25 plasma tubes around a helical antenna has proven dynamic beamwidth control, as well as 3-dimensional (3D) beam-steering capabilities over 20° around the end-fire direction [155]. Moreover, the use of plasma elements in reflectarrays is not limited to a planar lattice. For example, in [154] a numerical investigation is conducted on the feasibility of replacing the metallic truncated conical ground of the so-called helicone antenna with arrays of plasma tubes. The authors considered different configurations: U-shaped CCFLs, commercial fluorescent lamps, and a combination of fluorescent lamps, U-shaped CCFLs, and conical spiral plasma lighting tubes. They numerically confirmed that the plasma tubes could replace the metallic reflector to achieve the standard "helicone" antenna behavior. In this case, the use of the plasma tubes allows switching between two different radiation patterns. When the plasma reflector is on, the device behaves as a helicone antenna with higher radiation gain (or narrower beamwidth). On the contrary, when the plasma is off, the reflector is transparent, and the device behaves as a helical antenna with lower radiation gain (or wider beamwidth).

A relevant step forward in plasma-based reflectarrays is represented by solutions that aim to mimic arrays of metallic patches with tunable reflected phase capability. To this end, the first proposal is described in [18] and [149]. In these works different configurations of plasma reflectarrays are investigated numerically. Specifically, the square unit cells consisted of cubic glass boxes filled with argon gas. The fed antenna was a circular horn aperture antenna, and the authors proposed controlling the reflection coefficient phase by varying the plasma frequency (i.e., plasma density) of the energized gas. The work demonstrated the tunability of the reflection phase of the single unit cell from 0 to 300°. This range is large enough to achieve a beam steering offset of ±30°, yet obtained assuming hardly attainable plasma properties. Nonetheless, this work opened the way to other relevant numerical studies that encompassed even more advanced features, such as the digital control in space [157] and time [158]. In particular, the exotic unit cell proposed in [158] consisted of a dielectric ring-shaped vessel connected to a central cylinder through two rectangular arms, with an

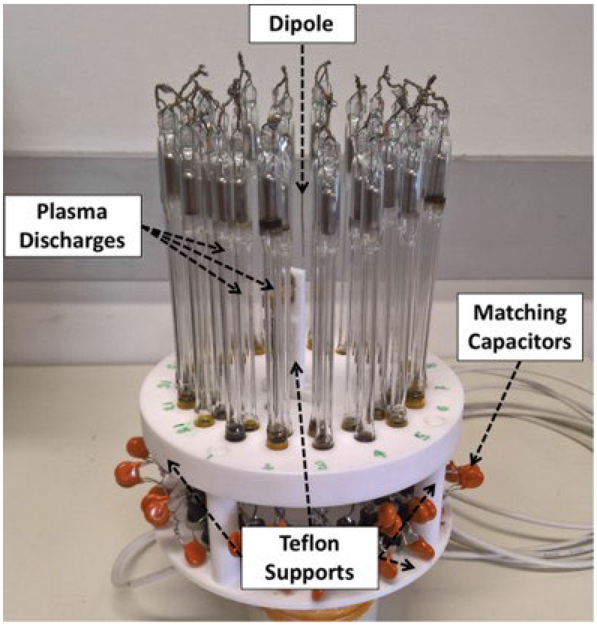

FIGURE 9. Circular plasma reflectarray [9].

overall cell size of 15 mm, approximately $\lambda/2$-long in the X-band, where the reflectarray was designed to operate. Because of that, the device adheres to the traditional design paradigm of reflectarrays, with phasing element sizes around half a wavelength. A similar design is proposed in [166].

Then, an extensive numerical analysis of the features achievable with planar arrangements of either cylindrical or squared vessels was carried out in [160], [161], [162], and [163]. These works showed that fine beam steering is achievable by the proper tuning of the phase response of adjacent cylindrical plasma columns [160], [161]. Other appealing features, such as simultaneous polarization control [162] and dual-band operations [163], were also demonstrated. These works first demonstrated the feasibility of such reflectarray structures at a realistic yet state-of-the-art range of plasma density, paving the way for the implementation of actual prototypes in the near future.

Table 4 presents a summary of the most relevant works on reflectarrays that have implemented plasma-based solutions.

C. TRANSMITARRAYS

Plasma tubes can be used as scatterers in transmitarrays to reconfigure antenna performance implementing beam steering. In [18] the design of transmitarray and reflectarray plasma antennas is presented where the unit cell elements consist of a cubic glass box filled with argon gas. In both cases, the steering of the EM waves is attained by adjusting plasma density. Moreover, in [167], dual-mode plasma reflectarray/transmitarray antennas utilizing hollow cylindrical tubes filled with plasma are presented. The study addresses the feeder blockage problem and explores the reconfigurable nature of plasma antennas. This concept is further expanded in [168] where a plasma-based intelligent omni-surface is proposed to operate in transmission, reflection or hybrid configuration.

The combined use of metallic radiators and plasma discharges can enable the development of a novel class of reconfigurable antennas. In [10] and [169] the optimization of a plasma-based transmitarray antenna using a particle swarm algorithm is discussed. The inclusion of a 2D lattice of 25 plasma discharges allows beam steering up to ±30° for an operation frequency of 1.07 GHz. This study evaluates the impact of metallic wires connected to the plasma tubes and realistic plasma parameters on the antenna performance. In [170] a metallic patch array coupled to a wall of fluorescent tubes is proposed for wireless communication. Plasma tubes are designed to ensure reconfigurability while maintaining good impedance matching. This study highlights the advantages of semiconductor switches in providing appropriate matching for various configurations. In [171] plasma tubes enable reconfiguring transmission and beaming properties of a guiding structure based on electronic bandgap.

Interestingly, plasma-transmitting surfaces have been proposed to control the polarization state of the scattered fields. In [144] and [172], the problem of combining beam steering and polarization control relying on a magnetized plasma is analyzed theoretically. Moreover, in [144] a numerical design is proposed to achieve linear-to-circular and cross-polarization conversion, or beam steering up to ±50°. This is feasible by maintaining decent values of gain, side lobe level, and reflection coefficient (e.g., gain $>$ 10 dBi). Another approach is pursued in [173], where the design and optimization of a plasma-based metamaterial polarizer for linear-to-circular polarization conversion in Ku-band is proposed. Specifically, linear-to-circular polarization conversion is possible energizing plasma.

Last but not least, plasma can also be used to realize frequency-selective surfaces. The work presented in [51] delves into the mathematical methods for analyzing scattered waves outside a cylinder and determining expansion coefficients using Bessel functions. Moreover, a proof of concept of the theory has been developed (see Fig. 10). It is worth mentioning that proof of concepts of plasma transmitarrays are presented just in this work and in [170] and [171].

D. PLASMA LENSES

Although many studies have been carried out on the application of plasma media in their conductive regime, for instance, for the realization of active GPAs and reflectors, there are limited works on the application of plasma media in their dielectric mode, especially as dielectric lens antennas [19]. However, at frequencies above the plasma frequency, an ionized gas behaves as a dielectric whose refractive index can be reconfigured, controlling the plasma density. Thus, plasma can be used for the realization of dielectric lenses with controllable focal lengths. Notably, there are two important differences between a lens made of

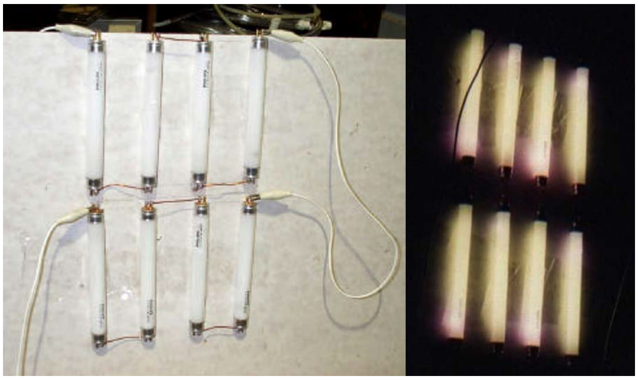

FIGURE 10. Plasma-based frequency selective surface [51] © 2007 IEEE.

ordinary dielectrics and a plasma lens. First, the refractive index of plasma is < 1; thus, a convex lens made of conventional dielectrics focuses a signal while a convex plasma diverges it. Second, plasma-based solutions allow controlling the focusing or steering of a RF beam, while conventional implementations present a fixed behavior. Interestingly, plasma lenses are particularly appealing for high-frequency applications such as millimeter [1] or sub-millimeter waves [87].

One of the first investigations into the concept of plasma lenses is reported in [62]. This study demonstrated to deflect a 36 GHz microwave beam by 25° without radically changing its shape or introducing significant sidelobes. The use of plasma tubes for building converging and diverging plasma lenses has been proved in [1]. This study experimentally demonstrated that a single plasma tube acts as a diverging plasma lens if the signal beam passes through its diameter. At the same time, two plasma tubes side-by-side form a converging (focusing) lens. Other important effects proved in [1] are the possibility of controlling the beamwidth by turning a plasma column on and off, as well as implementing beam steering by controlling the plasma ionization level. Theoretical analysis of cylindrical plasma columns to focus EM waves is later discussed in [174]. An important point to consider is that for a properly working lens, the wavelength should be small compared to the physical dimensions of the device. That is why millimeter-wave frequencies are used in [1] and [62].

In [175] a novel toroidal plasma lens is proposed as an alternative solution for electronic warfare antennas. The proposed solution aims to reduce the antenna profile and the RCS, thus minimizing the probability of target detection. The proposed architecture has been modeled, simulated, and optimized using a genetic algorithm. It has been concluded that an optimal gain enhancement of about 20 dBi can be achieved by a choice of $\epsilon_p = 0.4$–0.5. However, the study is solely based on numerical analysis and lacks experimental validation. Especially in [175], the effect of the plasma glass container that may result in relatively high backscattering is neglected. Further investigation and experimental validation of the potential of toroidal plasma tubes for enhancing the gain of antennas have been conducted in [176]. While the method seems to be applicable to different types of antennas, the study is focused on its applicability to improving the radiation gain of half-wave dipoles.

As mentioned, the dimensions of the plasma lens compared to the operating frequency limits the application of this technology to high frequencies (e.g., millimeter and sub-millimeter waves). Recently, the application of an array of plasma tubes to form reconfigurable lens antennas operating at relatively low frequencies and the associated analytical design procedure has been proposed in [19]. The study demonstrates that the proposed method can be used for the design of biconcave lens antennas with switchable radiation gain in the X-band. A one-dimensional prototype of the proposed lens has been designed, fabricated, and experimentally tested.

In [177] another very interesting application of plasma in microwave staring imaging is demonstrated. The key to this new radar scheme imaging is the uncorrelated wavefront modulation obtained using an array of plasma cells that can be randomly activated or deactivated. Thus, the plasma array can be considered as a reconfigurable lens that can produce multiple uncorrelated wavefronts.

Finally, the application of two colinear pump lasers with different foci overlapped in a gas jet to produce a holographic plasma lens is numerically studied in [178]. This system is capable of focusing or collimating a probe laser at intensities several orders of magnitude higher than the limits of a non-ionized optic. However, the study shows that exceptionally high plasma density is required, which may burden the realization of the proposed structure.

E. OTHER DESIGNS

This section includes examples of passive GPAs that cannot be fully identified in one of the previous categories. Specifically, one of the most appealing features of plasma is its stealth capabilities, particularly in the concealment of radiative elements. In other words, this consists of reducing the RCS of the antenna by covering the device with an adequately generated plasma cloud [11]. From an experimental point of view, this feature is confirmed in several essential works. For example, in [50], a low-pressure plasma discharge is employed to operate in the 2—18 GHz frequency range. Tests performed for normal and oblique incidence, either for TE or TM polarizations, confirm an RCS reduction up to more than 10 dB. The optimal performance is achieved for TM polarization, while in the case of TE polarization, the RCS reduction is less significant and strongly depends on the angle of incidence. Other examples include reflectarrays made of a circular or squared planar arrangement of plasma tubes [30], [179]. RCS reduction has been demonstrated experimentally also by coupling chessboard-like metasurfaces with either a plasma thin-layer [55], [64] or cylindrical discharge tubes [180].

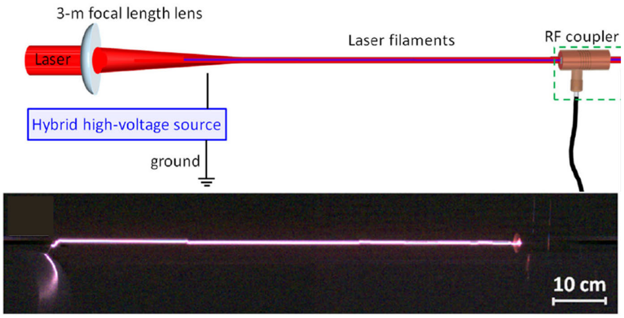

FIGURE 11. **Plasma antenna generated by laser. Reprinted from [67], with the permission of AIP publishing.**

Over the years, several authors proposed integrating thin plasma layers in metallic planar structures such as frequency selective surfaces [181], artificial magnetic surfaces [182], and metasurfaces [183], [184]. These solutions have been numerically demonstrated to outperform the corresponding RF shield without plasma for ameliorated bandwidth and, often, reduced thickness. Using column discharge tubes integrated parallel to a metasurface, yet independently controlled, was also numerically investigated in [185]. In this work, the metasurface was used to implement a waveguide rather than an antenna, and the plasma vessels were used to tune the electronic bandgap. At the same time, plasma vessels with complex shapes as unit cells of chessboard metasurfaces were also proposed to design artificial magnetic surfaces [186]. The design unit cell consisted of a millimeter-scale crossed arrow-shaped glass vessel filled with plasma over a grounded polyimide substrate with conformal capability. The tunability was achieved by changing the plasma density to control the conductivity of the plasma layer. Consequently, by increasing the plasma density, the resonance frequency and bandwidth of the surface are also increased. Similarly, in [187] a tunable and conformal frequency-selective surface is proposed. It is made from unit cells with a dielectric ring-shaped vessel connected to a central cylinder through two rectangular arms. Despite being well supported by an extensive numerical analysis, the complexity of the overall structure burdens a practical implementation of the latter two concepts.

Finally, a niche application deals with plasma integrated into transmit or reflectarray to generate vortex beams. In this case, an arbitrary reflection/transmission phase has to be achieved with a given spatial diversity at the surface. This can be obtained either by using stacked layers of magnetized uniform plasma slabs [188] or by employing layers of plasma elements with many angular sections [189]. These implementations have been investigated only numerically.

V. DIFFERENT IMPLEMENTATIONS

An overview of diverse antenna implementations based on plasma technology is presented. In this scenario, plasma antennas generated by lasers are a peculiar area of research at the forefront of communication technology. Following the pioneering concept proposed in [65], these antennas utilize intense laser pulses to create plasma channels in the air, forming conductive paths for electromagnetic signals. Specifically, attention has been paid to the ability of femtosecond filamentation for routing the radiation in atmospheric conditions [164]. During filamentation, a weakly ionized plasma column is obtained in the wake of an intense laser pulse, with an initial density of about 10^{22} m^{-3}, 100 μm diameter and a recombination time of the order of few nanoseconds. The limited lifetime of the plasma column represents this technology's main drawback. To overcome such limitation, an external electric field is proposed to increase the plasma lifetime up to 100 ns [66]. Moreover, recent works demonstrated an increase in the laser-guided plasma up to 2 ms using a hybrid high-voltage source. In particular, the high voltage discharge method allowed to profitably transmit a RF carrier of 173 MHz [67] (see Fig. 11).

Furthermore, besides serving as a suitable material for transmitting information signals, plasma holds significant potential for enhancing the performance of classical antennas [190], [191]. First, plasma can be employed to reduce the overall antenna dimension. Examples operating in the VLF/LF [192] or in the GHz frequency range [193] have been recently demonstrated. Second, when a sub-wavelength plasma layer covers an antenna, the radiation can be enhanced for certain plasma and geometrical parameters. For instance, in [194], a 60 mm plasma layer is designed to boost the radiation coming from an ellipse dipole antenna, demonstrating a gain of 10 dB higher than the free-space radiation case. The intensification effect was observed in the frequency range of 0.89–1.05 GHz. The same concept has been exploited also in [48], [56], and [195]. Notably, in [196] a harmonic oscillator model is derived to describe the enhancement of microwave radiation of an electrically small antenna when surrounded by a sub-wavelength plasma discharge. Theoretical studies about the influence of magnetic field on antenna performance are presented in [197] and [198].

Furthermore, it is worth underlining that another approach to create plasma is with the use of explosive [199], [200]. Explosive-based GPAs, despite their short-term existence, allow the creation of compact sources of EM signals and hence explore physical processes in the upper layers of the atmosphere. These antennas are notable for their simplicity and durability in atmospheric conditions, as well as their ability to create confined plasma columns. Explosive-based GPAs are designed to endure the shock and thermal stresses generated by the explosive process. They offer rapid operation and have relatively low mass and volume requirements. In [201], it has been experimentally demonstrated that a system with an energy of about 1 KJ is capable of producing a jet with a particle density of 10^{18} m^{-3} in free space with an active length of 150 mm. An explosive-based GPA is also reported in [202] for a mobile system. The proposed solution possesses advantageous characteristics, such as sharing a common energy source with the explosive generators. Moreover, the possibility of using a plasma jet for

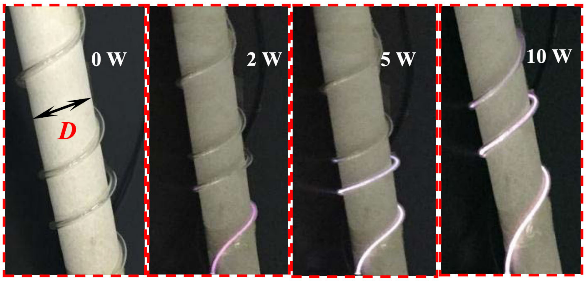

FIGURE 12. **Flexible plasma antenna [29] © 2007 IEEE.**

radio communication of hyper-sonic flying vehicles has been discussed in [203]. Additionally, the spark plasma antenna constitutes another valid approach for limiting the size and the mass of the transceiver setup [204].

As described so far, the use of plasma in the RF domain has been deeply investigated. However, the potential ability to manipulate the complex permittivity of the plasma discharge makes it intriguing for achieving reconfigurable RF components [1], [205]. For example, in [59] a plasma micro hollow cathode sustained discharge is experimentally tested to assess its feasibility as an integrated active component in antennas. This reconfigurable element exploits the permittivity change provoked by the presence of plasma. Plasma shells, namely hollow ceramic tubes that encapsulate an ionized gas, have been proposed as X-band switching components [206]. Specifically, a tunable spatial filter has been designed in [207] by integrating plasma shells strategically located to reconfigure the transfer function effectively.

Reconfigurability can benefit from a further degree of freedom, which is that of the use of flexible plasma antennas [29] (see Fig. 12). By utilizing a flexible system, different antenna characteristics can be adjusted, such as directivity, gain, bandwidth, and even polarization [208]. In [117] a GPA is fabricated using flexible materials and excited using a 5–20 kHz alternating current power supply. The antenna characteristics can, therefore, be controlled rapidly and easily by changing both the discharge parameters and the antenna shapes. Compared with a conventional GPA made of hard materials, the reconfiguration ability of the deformable GPA is highly enhanced. For instance, conversion between left-handed and right-handed circular polarization can be easily obtained by changing the winding directions of the discharge tube [29].

VI. EXPLOITATION OF PLASMA ANTENNAS

GPAs present special features with respect to metallic antennas [1]. This is due to the dispersive nature of plasma [6]. Indeed, its EM response depends on the operation frequency and plasma properties (see Eq. 1). As mentioned in Section II, the plasma density and neutral gas pressure are reconfigurable. Namely, the operation frequency [41] and radiation pattern [17] of GPAs can be controlled electronically. Similarly, plasma technology enables broad-band [36] and frequency selective [51] operations. Beyond that, the most unique property of GPAs is the capability to electrically "disappear" when plasma is not energized and reverts to the neutral gas state [14]. Thus, GPAs are a potentially disruptive technology for several application fields [1, Chap. 7]. Notable examples are 5G/6G networks [22], satellite communications [21] (see Fig. 13), biomedical diagnostics [24], and protection from electronic warfare [4].

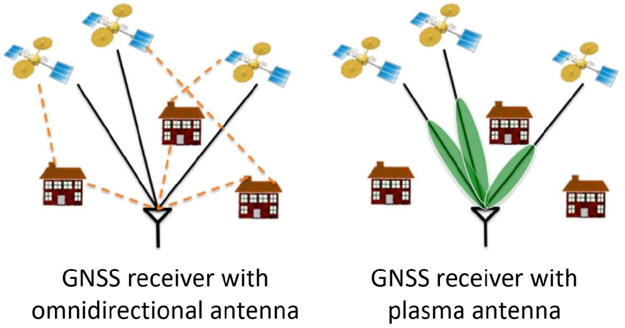

FIGURE 13. **GNSS scenarios for GPAs. Reprinted from [21] with permission from Elsevier.**

GPAs are reconfigurable and minimize the interference produced on other devices [51]. This is extremely appealing in the field of 5G/6G networks to reduce the overall cost of the system [1, Chap. 7]. Indeed, in a network based on smart antennas the signal processing software can be designed to steer the main radiation lobes towards the users, as well as reconfiguring nulls to minimize interference. At the same time, beam width can be adjusted to accommodate users who are in close proximity or at diverse locations [1, Chap. 7]. Even though the latter properties are shared with smart antennas available in the market [209], GPAs can provide unique contributions. In fact, plasma technology enable to dynamically reconfigure the operation frequency and the RCS of each antenna [3]. This could be exploited to reduce the number of multiple antennas stacked together to operate at diverse frequencies or to point in different directions [1, Chap. 7]. Clearly, considering the need to sustain GPAs with electrical power, the economical convenience of this technology shall be assessed case by case. GPAs targeting 5G/6G networks include plasma-based Intelligent Reflecting Surfaces (IRS) [12], [160] and Multiple-Input Multiple-Output (MIMO) systems [22].

GPAs have recently been proposed to improve satellite communications [9]. Global Navigation Satellite Systems (GNSS) allow to retrieve position with uncertainty lower than 1 mm [21]. Nonetheless, accuracy can decrease to tens of meters due to multipath errors, namely reflections on natural or artificial obstacles. GPAs can be employed in critical contexts (e.g., airborne antennas) to steer the beam toward the satellites' direction drastically reducing multipath [21]. In this framework, the main advantage of GPAs is the capability to reconfigure the radiation pattern electronically in a timeframe of 1 ms [8]. Such property can also be exploited in base stations to ease satellite tracking [9]. Regarding spaceborne applications, GPAs have been proposed to enable reconfigurability relying on a simpler architecture than phased arrays [210]. Moreover, GPAs represent an optimal solution to minimize the interference between antennas in close proximity, a situation easily found in space missions where volume and mass budgets are limited [14]. On the other hand, the power budget is a major constraint in assessing the feasibility of a spaceborne GPA [21]. Solutions targeting space applications include broad-band [161] and dual-band [163] reflecting surfaces, circular reflectarray [9], as well as curl [21], turnstile [21], and dipole [14] antennas.

The exploitation of GPAs for biomedical purposes has been assessed in [1, Chap. 16]. Specifically, plasma technology has been proposed to design the transmit coils for magnetic resonance (MR) [24]. The main advantage of this solution is that plasma can be turned on and off eliminating electrical interactions between coils [1, Chap. 16]. Moreover, GPAs could combine MR with Positron Emission Tomography (PET). In fact, PET is based on the detection of gamma rays whose attenuation is minimized if the RF antennas for MR are made with plasma and not metal [1, Chap. 16]. Moreover, a device called "phanotron" has been proposed to treat cancer cells [211], [212]. In-vivo tests have been performed to assess the anti-proliferation effect produced by varying the signal frequency. It is worth mentioning that this area of research is promising but at an early stage. For example, the efficiency of the system proposed in [24] is about one order of magnitude less than the equivalent metallic arrangement.

Military applications are particularly suited to exploit GPAs [1, Chap. 7]. In fact, a telecommunication system shall be stealthy, anti-jamming, and flexible to implement electronic warfare protection measures: GPAs offer all these features [1, Chap. 7]. As previously mentioned, stealth capability is the main advantage of plasma over metals [35]. Specifically, un-energized plasma elements are hard to detect by hostile radars since their RCS is reduced by tens of dB with respect to the equivalent metallic system [50], [110]. The adaptive nature of GPAs can be exploited to implement anti-jamming solutions [11]. For example, the main lobe can be narrowed, or nulls can be added to minimize disturbances [30]. At the same time, the beam can be widened if the user is relatively isolated or moves at a great speed. Performance flexibility, in turn, allows to reduce the computational effort for tracking [1, Chap. 7]. Finally, plasma is a good candidate to create confusion in warfare communications since it can be switched off within less than 1 ms [8].

In spite of all the advantages offered by GPAs, their widespread diffusion is still hindered by a major factor: the lack of commercially available plasma sources optimized for telecommunication purposes. In the literature, several solutions have been proposed to maximize the achievable plasma density [26], to improve reliability (e.g., mechanical robustness) [4], and to minimize power consumption [29]. Nonetheless, devices that synthesize all these characteristics are not available in the market. Just a few research centers worldwide [46] have the know-how to design, manufacture, and test plasma sources for telecommunication purposes and, in turn, to optimize GPAs. The picture is further complicated by the diversity of plasma discharges needed to implement different antenna concepts (see Section II-A). Thus, the commercial success of GPAs is intrinsically related to the acquisition of know-how from research centers on the design of plasma discharges and to the consequent technological transfer toward innovative companies.

VII. CONCLUSION

The literature on GPAs has been reviewed, highlighting recent advances and future perspectives within this technology. First, plasma has been analyzed in terms of EM response, and the techniques adopted to generate, measure, and simulate this material have been reviewed as well. The main analytical, numerical, and experimental results related to various GPAs have been examined. For the sake of clarity, antenna types have been classified as "active" or "passive", based on the primary function of the plasma elements: either to radiate EM signals or to manipulate them respectively. Additionally, less common GPA concepts, such as laser-based and explosive antennas, have been discussed, focusing on the pros and cons of various implementations. Lastly, the most attractive fields for the exploitation of GPAs have been evaluated, identifying antennas tailored for these applications.

The key takeaway from this review is that plasma antennas are a developing technology with unique capabilities. Their widespread diffusion is linked to two entangled aspects: (i) the development of plasma sources optimized for telecommunication purposes and (ii) the strategic identification of suitable application fields. In fact, a dedicated power budget will always be needed to operate a GPA, in spite of the wide possibilities of enhancing the performance and reliability of plasma sources. Of particular importance is recognizing applications where the extensive reconfigurability of GPAs, including the potential for "disappearing", can be truly game-changing. Hence, future work on GPAs should focus on advancing plasma technology while also customizing existing concepts to align with the specific requirements of sectors such as space and defense.

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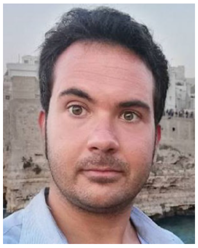

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