

Modeling and design of a plasma-based transmit-array with beam scanning capabilities

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ABSTRACT

This work presents the proof of concept of a novel plasma-based transmit-array antenna with beam scanning capabilities. The transmit-array operates above the GHz (precisely at 1.6 GHz) and is capable of steering its main lobe up to thirty degrees. A metallic half-wave dipole is used as the active element of the transmit-array, while twenty-five cylindrical plasma discharges are adopted to steer the beam of the antenna simply by turning them on or off. These passive elements are geometrically displaced in a triangular lattice.

A customized two-steps optimization strategy is used to choose the best geometrical parameters of the array and to select the subset of plasma discharges that maximizes the gain of the antenna for each desired scanning angle. Towards this aim, a particle swarm optimization is first used to optimize the geometrical parameters of the array, and then a genetic algorithm is adopted to select the optimal subset of plasma discharges that need to be turned on to scan the beam towards different directions.

The designed transmit-array was modeled in CST Microwave Studio, using realistic plasma parameters extrapolated from measurements of a fabricated plasma discharge prototype.

Introduction

Gaseous plasma antennas (GPAs) exploit partially or fully ionized gas to transmit and receive electromagnetic (EM) waves [1]. They consist of a dielectric vessel (e.g. glass or plastic) inside which a neutral gas is confined. By applying a suitable energy source to this gas, its particles become ionized and so they are free to move inside the vessel, thus making the gas conductive. Recently, there has been an increasing interest in the study and development of this type of antennas due to their numerous advantages with respect to conventional metallic antennas [1,2]. For example, GPAs are electrically (rather than mechanically) reconfigurable with respect to their operation frequency, input impedance, gain and bandwidth, on time scales of the order of microseconds to milliseconds. Another interesting advantage of GPAs derives from the fact that when the energizing source that ionizes the gas and creates the plasma is turned off, the gas reverts to its neutral state, thus being transparent to EM waves. This property makes plasma antennas very interesting for applications in which stealth is required. In fact, by designing a proper on-off scheme that minimizes the times in

which the antenna is transmitting or receiving signals (i.e., the times in which the plasma needs to be on), its radar cross section can be drastically reduced. Furthermore, plasma antennas are also transparent to EM waves whose frequency is above the plasma frequency. This leads to another interesting advantage of GPAs with respect to their metallic counterparts: they allow to reduce the interference between arrays that work at different frequencies.

The concept of GPAs is not new [3], but it has been gaining popularity only in recent years thanks to the development of novel plasma generation techniques. In fact, the first generation methods like DC/AC discharge [4] and laser-initiated atmospheric discharges [5] present some limitations, among which the most significant one is that the conductivity of the generated plasma is limited due to the moderate ionization level achievable with these techniques. The introduction of novel plasma generation techniques, like pulsing power techniques [6] and radio frequency surface wave [7], allowed to achieve more conductive gaseous plasma, leading to an increased interest in GPAs.

Looking at what can be found in literature, only few works about plasma antennas operating above the GHz have been presented [8]. The

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main reason behind this fact, is that GPAs require metal components to generate the plasma (e.g. electrodes and wires), and the dimensions of these components cannot be reduced below a certain threshold without compromising the quality of the generated plasma. This, in turn, implies that, as the operation frequency approaches the GHz, the dimensions of the metal parts become comparable to those of the antenna, thus compromising the GPA performance. Therefore, the vast majority of the works on plasma antennas deals with designs that operate below the GHz.

Another type of GPAs, that has not been thoroughly investigated, is the one in which plasma elements are used as *directors* to steer the beam towards different directions. Some works about plasma antennas with beam steering capabilities can be found in literature [9,10]; however, in these cases, the plasma elements are always used as *reflectors*, rather than as directors. On the other hand, the very few works dealing with plasma *directors*, present very basic designs that cannot achieve beam-steering capabilities [8].

This work presents the proof of concept of a novel plasma-based transmit-array antenna that works above the GHz. A complex arrangement of plasma tubes are used as directors in order to steer the main beam up to 30° from the direction of broadside. The plasma discharges are placed in a bi-dimensional lattice and their optimal distances have been determined through a particle swarm optimization. The array can achieve beam-scanning capabilities simply by turning on or off different subsets of plasma discharges: these subsets have been determined through the adoption of a genetic algorithm. The transmit-array has been designed in CST Microwave Studio. In order to provide a realistic model of the antenna, a plasma discharge has been fabricated and measured, and its properties were included in the software.

The rest of the paper is organized as follows: the realistic model of the plasma discharge is described in Section “Model of the realistic plasma discharge”, Section “Antenna modeling and optimization” reports the design of the transmit-array antenna, while Section “Numerical results” shows the obtained results. Eventually, some conclusions are reported in Section “Numerical results”.

Model of the realistic plasma discharge

A real plasma discharge has been fabricated and measured, in order to extrapolate the plasma characteristics that were included in CST for the design of the transmit-array. Fig. 1 shows the fabricated plasma discharge while its properties are measured by a microwave interferometer [11]. The discharge mainly includes a glass tube, two metallic electrodes, and the gaseous plasma that in this case is generated from an Argon-based mixture. The glass vessels are custom-made, and the electrodes were chosen to satisfy two constraints: (i) they need to be as small as possible in order not to increase significantly the discharge

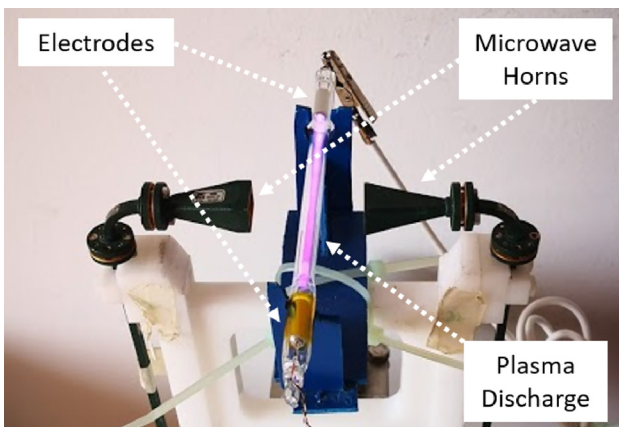


Fig. 1. Characterization of a plasma discharge by means of a microwave interferometer.

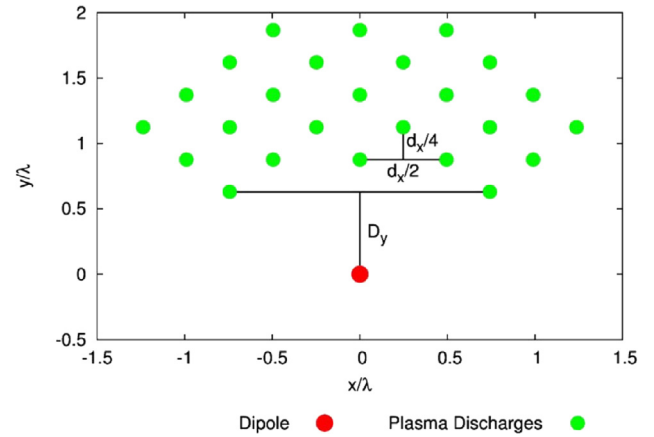


Fig. 2. Top view of the transmit-array antenna layout.

length, (ii) they need to be large enough to be capable of igniting and sustaining an electrical current that can generate a stable and conductive plasma. A good compromise for the dimensions of the electrodes (of cylindrical shape) was found to be 2 cm in length and 4 mm in diameter.

The plasma is generated by exciting the neutral gas mixture with approximately 10 W of RF power (operation frequency $f \approx 1$ MHz). Once the gas has been excited, its properties in terms of gas density and pressure are measured thanks to an interferometric system (as depicted in Fig. 1). From this data, it is possible to extract the correspondent plasma and collision frequency that are then used to model the plasma in CST Microwave Studio ($\omega_p = 178.4$ GHz and $\nu = 103.28$ MHz).

Antenna modeling and optimization

Fig. 2 reports the top view of the proposed transmit-array design. This consists of an active metallic dipole (red circle at the bottom of the figure) and $N = 25$ cylindrical plasma discharges (green circles) arranged in a triangular lattice. The number of the discharges has been selected in order to simulate a realistic prototype, namely a device in which the power used for to generate the plasma is always below 250 W. The plasma discharges length and diameter are set in such a way that the plasma cylinders resonate at the operation frequency $f = 1.6$ GHz, following the procedure described in [8]. This frequency has been chosen since it is the highest that can be reached by the cylindrical plasma discharges, considering the available state-of-the-art plasma generation technology and our custom-made fabrication process. In order to provide a realistic model of the antenna, the plasma inside the cylinders has been modeled in CST as a dispersive Drude material, using the values of plasma and collision frequency ($\omega_p = 178.4$ GHz and $\nu = 103.28$ MHz, respectively) that were extrapolated from the measurements of a real plasma discharge, as described in the previous section.

In order to determine the best geometrical arrangement of the different plasma discharges, a two-step optimization procedure is proposed on the basis of the outcomes and guidelines of [12–14].

First, the distance D_y between the active dipole and the plasma dipoles, and the distance $d_x/2$ between adjacent plasma cylinders (see Fig. 2) are optimized. Due to the non-convexity of the problem under examination, a global optimization technique based on a Particle Swarm Optimization (PSO) approach is adopted. This collaborative optimization algorithm, inspired by the social behavior of bee swarms, is particularly suitable for optimization problems dealing with real and continuous variables, as it is in this case. The parameters considered in the optimization are d_x and D_y , while the other fixed parameters are the plasma and collision frequency $\omega_p = 178.4$ GHz and $\nu = 103.28$ MHz, the length $l_p = 49.25$ mm and the radius $r_p = 1.25$ mm of the plasma

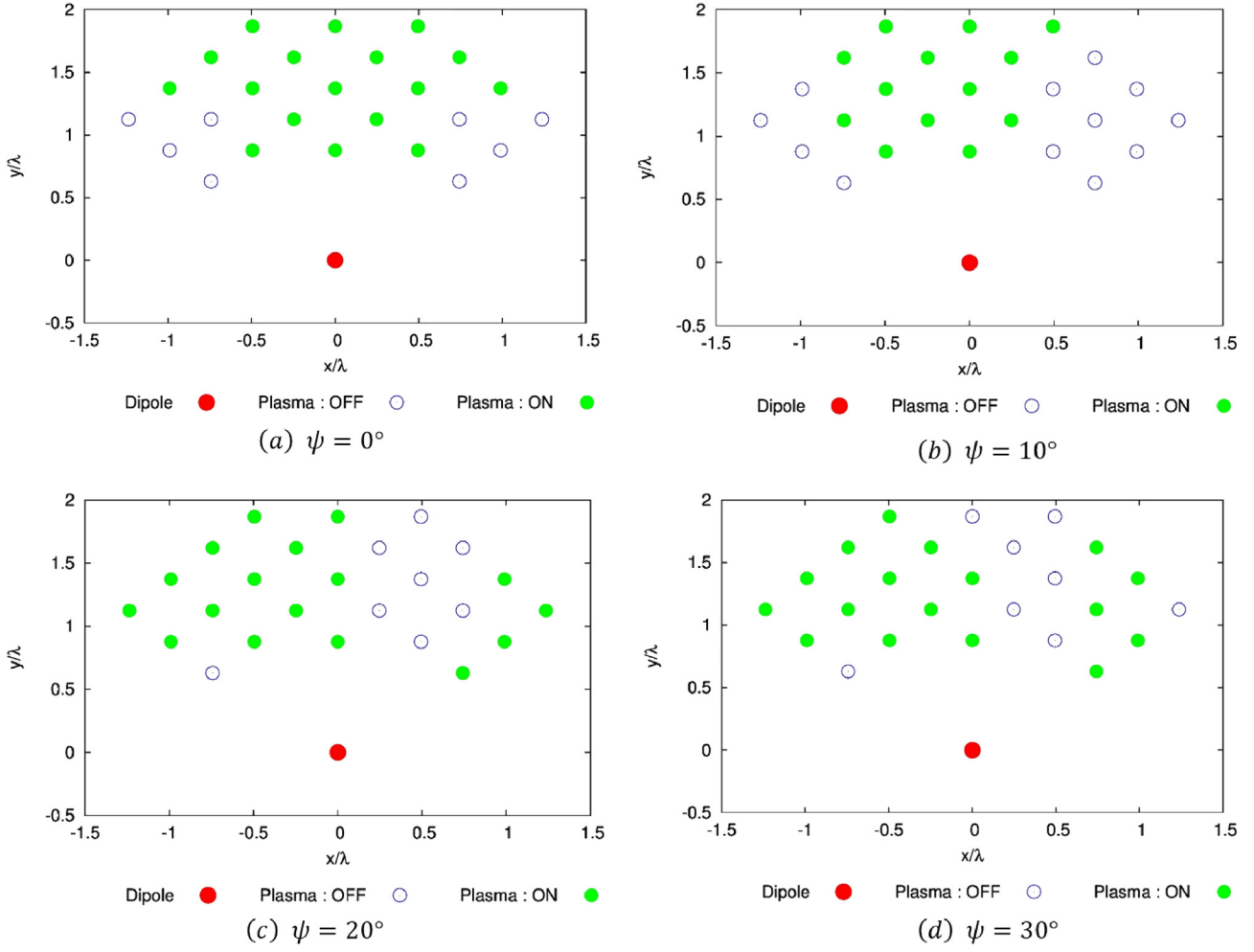


Fig. 3. Optimized arrangement of on/off discharges to steer the beam of the array towards the directions $\phi = 90^\circ + \psi$, with $\psi \in \{0^\circ, 10^\circ, 20^\circ, 30^\circ\}$ (Figures (a), (b), (c), (d) respectively).

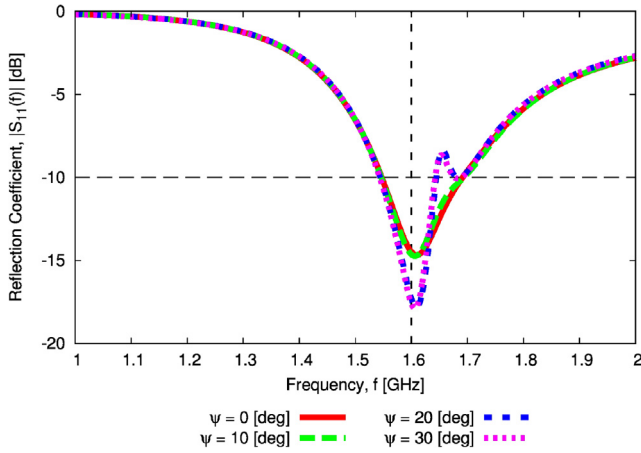


Fig. 4. Magnitude of the reflection coefficient for the four steering angles $\phi = 90^\circ + \psi$, with $\psi \in \{0^\circ, 10^\circ, 20^\circ, 30^\circ\}$.

discharges (i.e., of the region filled with the gas), the length of the active metallic dipole $l_d = 85.45$ mm, the gap $g = 1.4$ mm between its two arms, and its radius $r_d = 0.45$ mm.

Given this information, the optimization problem can be addressed by the minimization of the following cost function:

$$\Phi(d_x, D_y) = \frac{1}{G(\theta = 90^\circ, \phi = 90^\circ)} \quad (1)$$

where $G(\theta = 90^\circ, \phi = 90^\circ)$ is the gain of the array in the broadside direction. The PSO leads to the optimized value $d_x = 191.61$ mm and $D_y = 121.54$ mm.

Once the best values of d_x and D_y are determined, another optimization needs to be carried out in order to find the optimal subset of plasma discharges that need to be turned on in order to scan the beam towards a specific direction. Therefore, another set of optimizations is performed for each desired scanning angle of the antenna, i.e., $\phi = 90^\circ + \psi$, with $\psi \in \{0^\circ, 10^\circ, 20^\circ, 30^\circ\}$. Since the optimal positions of the elements have been determined in the previous step for the broadside direction, this optimization addresses the issue of deciding which plasma bars should be on and which should be off. Therefore, due to the binary nature of the problem, a genetic algorithm (GA) is a good choice as far as the optimization approach is concerned. The discharges in the off-state have been modeled as cylindrical bars filled with vacuum instead of plasma material. In this case, the cost function to be minimized is defined as:

$$\Phi_\psi(d_x, D_y) = \frac{1}{G(\theta = 90^\circ, \phi = 90^\circ + \psi)} \quad (2)$$

where $\phi = 90^\circ + \psi$, with $\psi \in \{0^\circ, 10^\circ, 20^\circ, 30^\circ\}$ is the desired angle of scanning. The four optimal configurations resulting from this second set of optimizations are depicted in Fig. 3.

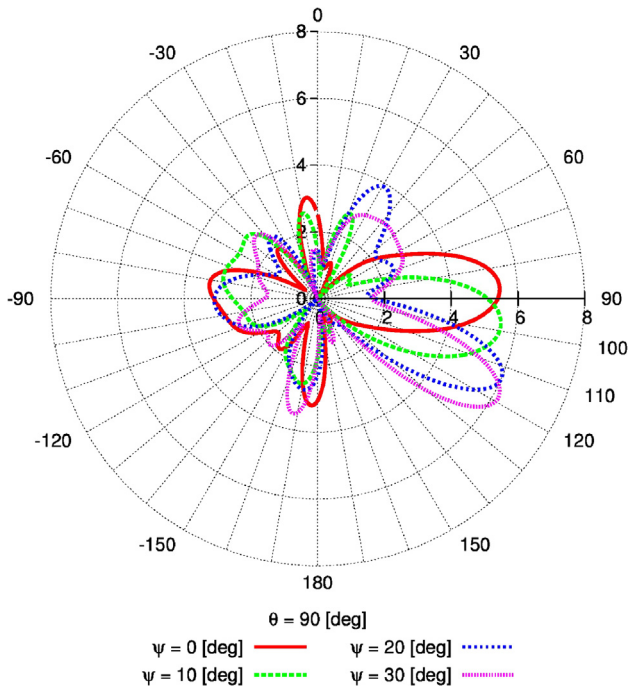


Fig. 5. Gain (in dB) of the optimized transmit-array at $f = 1.6$ GHz on the $\theta = 90^\circ$ plane for the four steering angles $\phi = 90^\circ + \psi$, with $\psi \in \{0^\circ, 10^\circ, 20^\circ, 30^\circ\}$.

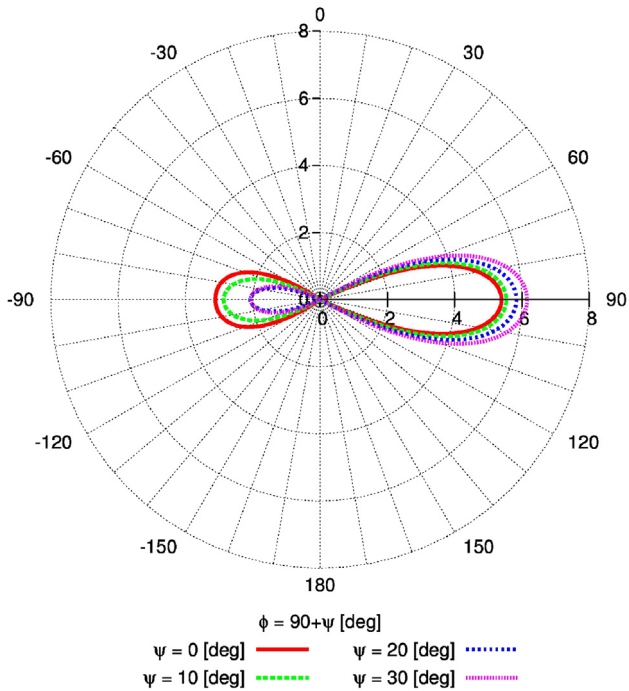


Fig. 6. Gain (in dB) of the optimized transmit-array at $f = 1.6$ GHz on the four planes $\phi = 90^\circ + \psi$, with $\psi \in \{0^\circ, 10^\circ, 20^\circ, 30^\circ\}$.

Numerical results

The performance of the four optimal plasma transmit-array geometries (depicted in Fig. 3) are reported in Figs. 4–6. Fig. 4 depicts the magnitude of the reflection coefficient for each of the four configurations. It can be observed that the $|S_{11}|$ behavior undergoes some slight modifications as the subset of active plasma discharges changes. However it remains below -10 dB around the operation frequency

$f = 1.6$ GHz in all the four cases.

As far as the gain is concerned, Figs. 5 and 6 show the polar plot (in dB) on the $\theta = 90^\circ$ and $\phi = 90^\circ$ planes respectively. It can be seen how changing the set of plasma discharges that are turned on, the transmit-array can scan the main beam towards four different directions up to 30° . It can also be observed that the main lobe gain increases as the beam is scanned away from the direction of broadside, and this is mainly caused by the narrowing of the beam. The efficiency of the antenna for $\psi = 0^\circ, 10^\circ, 20^\circ, 30^\circ$ is 90.05%, 90.17%, 90.66%, 90.65% respectively.

Another thing that can be noticed is that there is a significant back-side lobe. This can be mitigated by enhancing the present design with the addition of a reflector; however, this would require another set of optimizations and, therefore, it is outside the scope of this work.

From the observation of Figs. 5 and 6, it is clear that the proposed transmit-array can achieve reconfigurability with respect to its radiation pattern simply by turning on/off a subset of plasma discharges.

Conclusions

This work has presented the proof of concept of a novel plasma-based transmit-array antenna working at 1.6 GHz. The proposed transmit-array can scan its main beam up to thirty degrees from the direction of broadside simply by turning on or off different subsets of plasma discharges.

In order to model the antenna, a two-steps optimization has been run on the array geometry: first a particle swarm optimization has been taken into account to optimize the distances between the elements; then a genetic algorithm has been adopted to select the optimal subset of plasma discharges that need to be turned on in order to scan the array beam.

Realistic plasma discharge parameters were used in the full wave solver thanks to measurements performed on a fabricated prototype.

CRediT authorship contribution statement

Giulia Mansutti: Methodology, Writing - original draft. **Paola De Carlo:** Methodology, Funding acquisition, Writing - review & editing. **Mohammad A. Hannan:** Methodology, Software, Writing - review & editing. **Federico Boulos:** Methodology, Software, Writing - review & editing. **Paolo Rocca:** Methodology, Supervision, Writing - review & editing. **Antonio-D. Capobianco:** Methodology, Supervision, Writing - review & editing, Funding acquisition, Project administration. **Mirko Magarotto:** Methodology, Writing - review & editing. **Alberto Tuozi:** Methodology, Funding acquisition, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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