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Computational Analysis of the Effects of Power on the Electromagnetic Characteristics of Microwave Systems with Plasma

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Abstract

The scaling of microwave plasma technologies from successful laboratory demonstrations to larger industrial applications usually involves an increase in microwave power. This upgrade is accompanied by a higher electron density (and electric conductivity) of the plasma that often limits the power efficiency of the device. In this paper, we address this issue through a focused computational study of electromagnetic characteristics of a microwave system containing plasma. Our approach employs finite-different time-domain analysis supported by a simple model which characterizes the plasma medium using plasma frequency and the frequency of electron-neutral collisions. Based on experimental data for electron density with respect to power, the plasma frequency is generated as a linear function of power, thus enabling a direct understanding of how frequency characteristics of the reflection coefficient and patterns of the electric field may vary for different power levels in a variety of plasma scenarios. For a cavity modeled after conventional plasma applicators, computational results illustrate complex behavior of the field with respect to power. When the power is increased, energy efficiency may decrease, remain low, or increase depending on where the operating frequency stands with respect to the system's resonances. The proposed modeling approach identifies the system parameters which are most impactful in tuning the system to resonance, thus informing the design variables for subsequent computer-aided design of the scaled system.



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1. Introduction

Recent years have seen significant developments in diverse microwave (MW) plasma technologies such as surface processing of semiconductor components, diamond synthesis, hydrogen production, nitric acid synthesis, decomposition of CO₂, plasma antennas, plasma-based intelligent reflecting surface, and other innovations [1–12].

When designing MW plasma technologies to be operational on an industrial scale, one needs to deal with multiple interrelated issues. This creates significant challenges and often requires special treatment [13–17]. The conventional approach usually involves constructing the scaled-up system (guided by the basic laws of physics and engineering perceptions), applying desirable characteristics to it, and analyzing the performance after. Successful ventures of this type are reported in the literature [13,14], but technical aspects

of these works are project-specific. In the absence of a systematic approach, scaling issues are addressed nearly from scratch for each individual process or application.

One of the challenges associated with industrial scaling is a lack of control over the shape of the plasma volume. To this end, it was demonstrated that plasma can be made sufficiently uniform through the proper use of certain MW plasma sources [18]. An approach based on the use of solid-state generator arrays was suggested in [19].

Another challenge designers may face is a limitation on power levels. The increase in power also increases the electron density (and hence the electric conductivity) of the plasma. This generally worsens the system's coupling and cuts the energy efficiency of the system. It is therefore implied that there is an upper limit on the scaling of MW plasma technology.

When developing new MW plasma systems and processes (or scaling them up), it may be logical for designers to turn to guidance from computer modeling. In reported simulations, distributions (and maximum values) of electron density were computed for select values of power [20–22], gas temperature [23], pressure [23–25], and time [24,26] using the Finite Element Method (FEM) implemented in COMSOL Multiphysics [27]. In these multiphysics simulations, the underlying electromagnetic (EM) processes were modeled in frequency domain (FD). In computational electromagnetics, FD FEM is generally known for its mathematical robustness and flexibility in geometry handling. It is also known, however, for demanding exceptional computational resources, for limited instructiveness, and as a result, for being frequently impractical for computer-aided design (CAD) of electrically large systems. In computational studies of microwave power engineering, EM modeling using the Finite-Difference Time-Domain (FDTD) technique is widely recognized to be more informative, often more accurate, and less computationally expensive than FEM FD simulations [28–30].

On the other hand, as a numerical method proposed for solving Maxwell's equations, the FDTD technique provides limited options for multiphysics modeling [30]. These circumstances confront the modeler with a choice based on the ultimate goals of modeling—either to prioritize the vital need for estimates of physical processes induced by the electromagnetic field (even having paid a very high price for it), or a better understanding of the primary electromagnetic processes in the background of a complex multiphysics phenomenon and acquiring data on their possible control and optimization.

This paper explores the latter approach in response to the conventional challenge of power limitation for scaling of MW plasma systems. By utilizing the resources of FDTD EM modeling, we suggest a systematic analysis of EM processes to clarify the options for dealing with this constraint and mitigating the related technical issues. The recently proposed simplified characterization of MW plasma [31,32] has laid groundwork for the use of the FDTD technique to determine the operational bounds of applicators with plasma and assist in the CAD of such devices. With the motivation to demonstrate the benefits of this approach in dealing with the impact of MW power, we:

- (i) Extend the plasma model [32] by adding a direct approximation of the link between plasma frequency and MW power;
- (ii) Perform an instructive computational analysis of a 2.45 GHz system resembling certain plasma applicators.

Computations are executed with the use of the FDTD simulator QuickWave (version v2018) [33]. They explicitly demonstrate, for the first time, how the level of MW power may influence the EM characteristics of a MW device containing plasma—namely, the field patterns and reflections. Computational results reveal the absence of a straightforward dependence between decreased energy coupling and increased power but suggest an opportunity to take advantage of the resonant properties of the system to improve coupling and energy efficiency.

2. Computational Method

2.1. Plasma Model

EM time-domain simulation of MW systems with plasma has previously been limited by the challenges associated with the generation of input parameters to characterize the plasma medium. The considerable complexity of the underlying physics is in part accountable for this shortcoming. Initial ideas to simplify characterization of MW plasma for FDTD EM modeling were outlined in [31], and a detailed roadmap to generating FDTD inputs for plasma media is given in [32]. In this approach (illustrated by the flow chart in Figure 1), a plasma medium is characterized by electric conductivity σ , which is defined by the loss factor ϵ'' as

$$\sigma = 2\pi f \epsilon_0 \epsilon'', \quad (1)$$

where ϵ_0 is the permittivity of free space, and f is the operating frequency. Since MW plasma is not only lossy but also a dispersive medium, the loss factor, following the Lorenz–Drude model, is expressed as:

$$\epsilon'' = \frac{2\pi f_p^2 \gamma}{f[(2\pi f)^2 + \gamma^2]}, \quad (2)$$

where f_p is the plasma frequency and γ is the electron-neutral collision frequency. In (2), f is generally one of the standard ISM frequencies, so the compilation of input data for a plasma medium can be reduced to the definition of collision frequency and plasma frequency.

By assuming that the MW plasma is highly collisional and dominated by collisions between electrons and heavy particles, the collision frequency γ can be represented as:

$$\gamma = n_g v_e \sigma_{en}, \quad (3)$$

where n_g is the neutral gas density, v_e is the average thermal speed of the electrons, and σ_{en} is the cross-section of electron-neutral collisions. As for plasma frequency, it can be expressed as a function of electron density N as:

$$f_p = \frac{q}{2\pi} \sqrt{\frac{N}{m\epsilon_0}} \approx 8.97\sqrt{N} \quad (4)$$

where m and q are the mass and the charge of an electron.

Plasma parameters n_g , v_e , σ_{en} (in (3)) and N (in (4)) depend on operational parameters of a MW plasma system, such as power P_0 , pressures P , and the gas flow rate R . Unlike earlier dependencies, however, the connection between these parameters and operational parameters is system-specific. If the model is to be a practical tool of design, the relationships of n_g , v_e , σ_{en} and N to P_0 , P , and R must be determined by either experimental diagnostics or literature-based review of similar systems and processes. In practice, experimental determination is often challenging, and at times it is not possible. To overcome this data uncertainty, [32] describes a literature-based approach to estimate values of n_g , v_e and σ_{en} for different plasma scenarios. What remains then is to understand how N depends on P_0 for a broad range of values and system types.

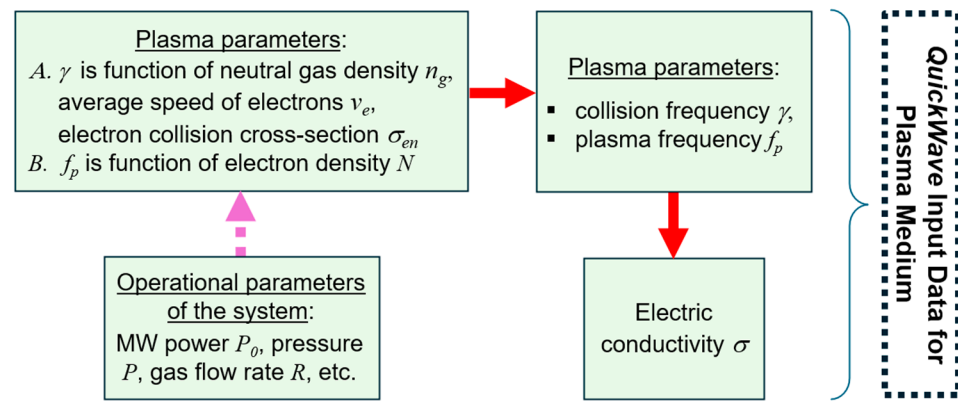


Figure 1. Determination of input data for plasma medium in the EM FDTD model (adapted from [32]). The system-specific dependencies of plasma parameters on operational parameters are shown by the dotted arrow.

2.2. Plasma Frequency as Function of Power

In order to explore the impact of systematically increasing input power on the electric field and the reflection coefficient of a system, we follow the plasma model introduced in [30] and extend the ideas originally coined in [34] to approximate an explicit link between P_0 and f_p .

In general, electron density is a system-specific function of MW power. According to the experimental data in the literature, the relationship $N(P_0)$ is typically close to linear. Based on measurements reported for three independent systems in [35–37], a set of three respective linear equations can be formulated using a first order regression of the experimental data provided:

$$N \cdot 10^{-23} [m^{-3}] = 1.12 \cdot 10^{-3} P_0 [W] + 2.57 \quad (5)$$

$$N \cdot 10^{-23} [m^{-3}] = 7.54 \cdot 10^{-6} P_0 [W] + 8.28 \cdot 10^{-4} \quad (6)$$

$$N \cdot 10^{-23} [m^{-3}] = 2.32 \cdot 10^{-10} P_0 [W] + 5.22 \cdot 10^{-7} \quad (7)$$

By combining (5)–(7) with (4), another regression can be applied to linearly approximate the relationship between plasma frequency and MW power:

$$f_p [\text{GHz}] \approx 0.938 P_0 [W] + 4.56 \cdot 10^{-3} \quad (8)$$

$$f_p [\text{GHz}] \approx 0.213 P_0 [W] + 91.5 \quad (9)$$

$$f_p [\text{GHz}] \approx 0.000432 P_0 [W] + 2.05 \quad (10)$$

Expressions (8)–(10), along with (1)–(3) and values for n_g , v_e and σ_{en} fixed by the methods in [32], set up explicit conditions for σ in each of the MW plasma systems described by [35–37]. While, in general, a higher input power can indirectly lead to a higher plasma frequency, this dependency, for many different reasons, may be non-linear. However, given the diversity of the devices behind these measurements of $N(P_0)$, we assume that the corresponding values of f_p and σ (Table 1) depict a broad range of how key FDTD input parameters can realistically depend on MW power.

Table 1. Values of plasma frequency and electric conductivity based on experimental data [35–37].

P_0 [W]	(8) & (1) and (2)		(9) & (1) and (2)		(10) & (1) and (2)	
	f_p [GHz]	σ [S/m]	f_p [GHz]	σ [S/m]	f_p [GHz]	σ [S/m]
10	4569	10,021	85.4	3.5	2.05	0.0020
100	4654	10,395	113	6.13	2.09	0.0021
500	5029	12,138	193	17.8	2.27	0.0025
1000	5498	14,508	260	32.4	2.48	0.0030
1500	5967	17,088	313	47.0	2.70	0.0035
2000	6436	19,880	358	62.6	2.91	0.0041

3. Plasma Applicator and Its Model

To demonstrate functionality of the extended plasma model and usefulness of the related FDTD simulation, we perform a computational study of a generic 2.45 GHz MW applicator (Figure 2). In this applicator, the plasma is ignited in a gas enclosed in a cylindrical quartz tube coaxially positioned in a metal cylinder. The cylinder is connected to an exciting rectangular waveguide (WR284) oriented such that its wide wall is parallel to the y -axis. This entire setup is placed on top of a larger cylindrical cavity which serves as a reactor for the intended application. The system is designed to resemble some typical MW apparatuses containing plasma [8,38,39]. The fixed dimensions of the applicator are $H = 200$ mm, $R = 300$ mm, $D = 100$ mm, $L = 264$ mm, and $m = 12$ mm, as defined in Figure 2. To isolate the impact of the plasma, the processed material (which would normally be situated in the larger cylinder) is not included. The model is built for the FDTD simulator QuickWave and exploits a non-uniform mesh with 1.2 mm cells in air and 0.25 mm cells in the quartz and plasma.

To define the electron-neutral collision frequency γ , we use formula (3). In accordance with [32], for applications at low and near atmospheric pressures, the neutral gas density can be assumed to be $n_g = 1.94 \times 10^{22} \text{ m}^{-3}$ or $n_g = 2.25 \times 10^{24} \text{ m}^{-3}$, respectively. Based on the mean of a Maxwell Boltzmann distribution, the average speed of electrons can be approximated as $v_e = 1.06 \times 10^6 \text{ m/s}$. Lastly, if the majority of collisions are assumed to be purely elastic, the electron-neutral collision cross-section can be roughly estimated by the circular area set by the atomic radii of the neutral gas used in ignition. Using these values, Table 2 contains the values of γ for Helium, Argon, and Xenon at low and near atmospheric pressures.

In our exploration, we assume that the relationship between plasma frequency and MW power is defined by (9) and choose the corresponding values of f_p and σ from Table 1. The values for the electric conductivity in this case are high (for $P_0 > 500$ W, σ is larger than 18 S/m) and notably exceed σ for typical lossy dielectric materials. The volume occupied by plasma medium in the system is also not negligible size, so it is expected that the system will behave like a resonant structure.

Table 2. Calculated values of collision frequency for three gases at different pressures.

Pressure	γ [GHz] (by (3))		
	He	Ar	Xe
Low	0.06	0.33	0.75
Near atmospheric	7.2	37.8	87.5

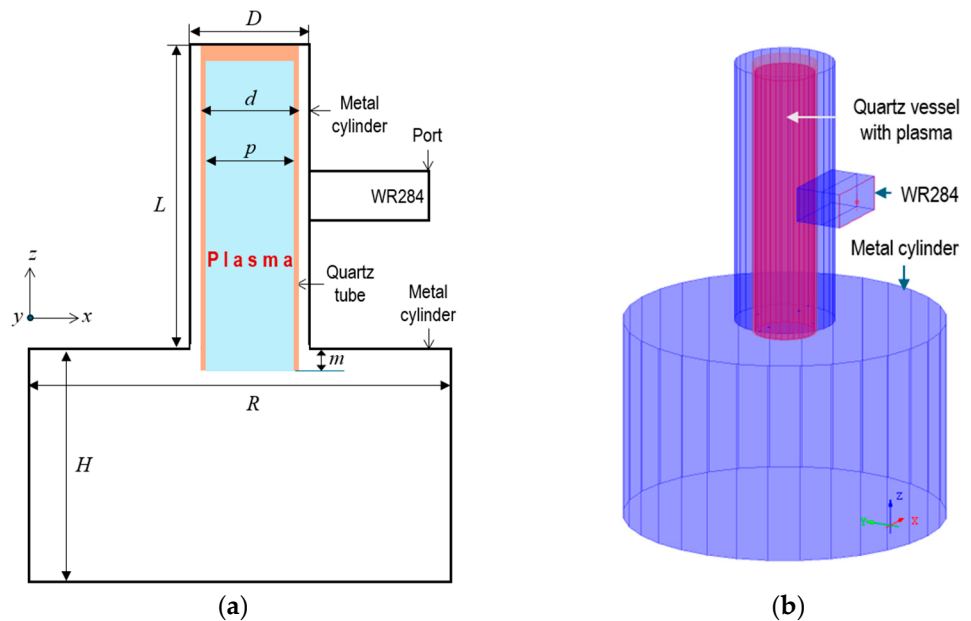


Figure 2. MW plasma system: layout and geometrical parameters (a) and 3D view of the system in the QuickWave GUI (b).

4. Results of Computational Analysis

4.1. Impact of Microwave Power

In Figure 3, the curves are shown for a fixed geometry of the plasma vessel and varied levels of MW power. As P_0 increases, the behavior of absorption (and hence energy efficiency of the applicator) appears to depend on where the operating frequency f_0 is with respect to the system's resonances.

At certain frequencies, the reflections rise when the power increases. At $f = 2.485$ GHz, when MW power increases from 10 to 1500 W, $|S_{11}|$ surges and efficiency η (such that $\eta = [1 - |S_{11}|^2] 100\%$) drops from 90 to 4.7%.

However, at most frequencies, if f is not near a resonance, the reflection is very high (and the coupling is very poor) regardless of the level of P_0 . For example, in Table 3 when $f = 2.45$ GHz, η is limited within 1.8 to 5.7%. Moreover, at some frequencies, when the power increases, the reflection coefficient actually decreases and energy efficiency goes up. One such case is $f = 2.586$ GHz. For this frequency, when P_0 is increased from 10 to 1000 W, η increases from 11 to 78%. This rather counterintuitive behavior is a direct consequence of the fact that the shapes and positions of resonances vary with the conductivity of the plasma medium, which depends on P_0 . The insert in Figure 3 depicts the formation of such resonances which make this effect possible.

Table 3. Magnitude of the reflection coefficient [-] and corresponding energy coupling [%] at different operating frequencies.

Power P_0 [W]	$ S_{11} $					η				
	10	100	500	1000	1500	10	100	500	1000	1500
$f = 2.450$ GHz (Δ)	0.971	0.981	0.983	0.991	0.980	5.7	3.8	3.4	1.8	4.0
$f = 2.485$ GHz	0.322	0.809	0.954	0.965	0.976	90	35	9.0	6.9	4.7
$f = 2.586$ GHz (o)	0.945	0.932	0.716	0.473	0.717	11	13	49	78	49

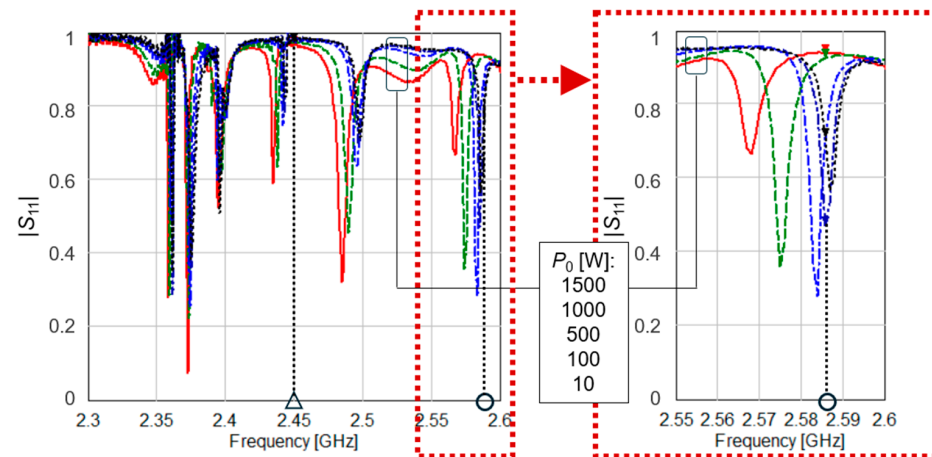


Figure 3. Frequency characteristics of the reflection coefficient in the system in Figure 2 for MW power in the range from 10 to 1500 W (σ by (9), Table 1); $d = 58$ mm; $p = 54$ mm; plasma in Argon at low pressure; $f = 2.45$ GHz is marked by Δ ; $f = 2.586$ GHz is marked by $\circ$.

4.2. Influence of Plasma Geometry

Apart from the conductivity of the plasma medium, geometric parameters of the system are also capable of altering the profiles of the $|S_{11}|(f)$ characteristics. The curves in Figure 4 obtained for different geometrical characteristics of the plasma vessel show that both the diameter of the plasma cylinder p and the thickness of the quartz wall $t = (d - p)/2$ can be impactful enough to completely modify the system's resonances. As demonstrated in Figure 4a,c,d, increasing p from 38 to 54 mm results in a substantial change in the $|S_{11}|(f)$ characteristics; these changes include the appearance of new, and wider, resonances. As seen in Figure 4b,d, altering t from 2 to 10 mm eliminates two deep resonances in the frequency range from 2.4 to 2.5 GHz (around 2.42 and 2.47 GHz) and creates two others of lower depths (near 2.41 and 2.44 GHz).

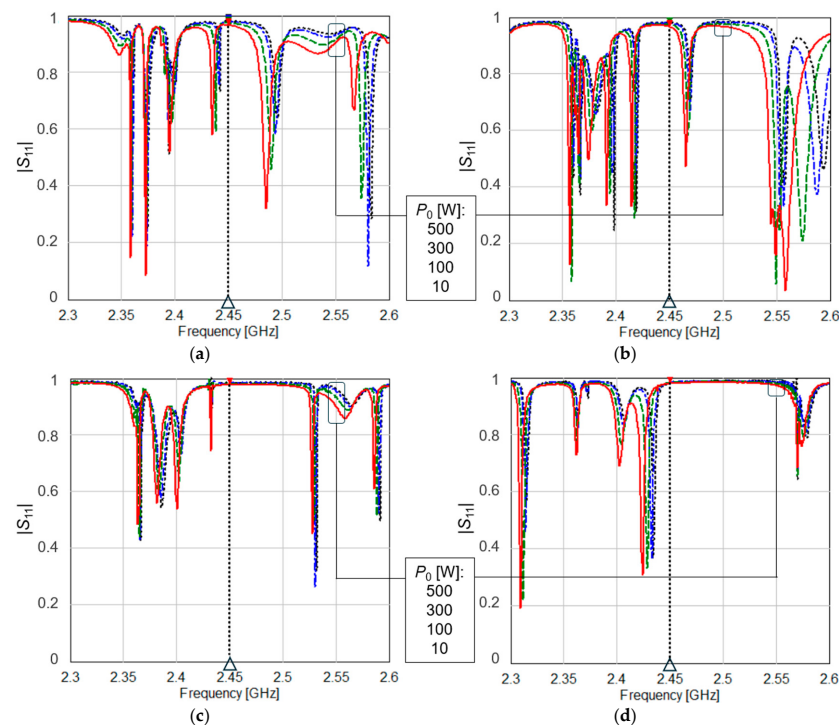


Figure 4. Frequency characteristics of the reflection coefficient in the system in Figure 1 for microwave power in the range from 10 to 500 W (σ by (9), Table 1); plasma in Argon at low pressure; $d = 58$ mm (a,b), 50 mm (c), 42 mm (d); $p = 54$ mm (a), 46 mm (c), 38 mm (b,d).

4.3. Effect of Gas

The $|S_{11}|(f)$ curves shown in Figure 5 are simulated for a fixed power and geometry, and a variety of neutral gases with a wide range of atomic radii (from He to Xe). It is seen that across the gases selected, the positions and the depths of the resonances are practically identical. Different gases used in plasma ignition are known to have an impact on plasma density, space charge, electron sheath thickness and other physical aspects of plasma, which also influence the EM field [40,41]. From the EM perspective however, the MW system considered (Figure 2) seems to be nearly independent of the gas in which plasma is ignited. This is consistent with the fact that, in the framework of the proposed approach, the gas is only explicitly introduced into the FDTD model through the value of σ_{en} (and effectively γ) in accordance with (1) and (2). It is ultimately less impactful on σ than N (through f_p).

4.4. Effect of Pressure

In contrast to the characteristics in Figures 3–5, the graphs in Figure 6 are computed for higher (near atmospheric) pressure. The pressure under which a MW system with plasma operates is represented in the FDTD model through n_g in formula (3), within the definition of collision frequency γ . Unlike σ_{en} in (3), which numerically represents the choice of neutral gas and varies at most within one order of magnitude, n_g is capable of varying within two orders of magnitude. Direct comparison of Figures 4a and 6b suggests that the two-order magnitude difference of n_g is sufficient to see shifts and deformations in the profiles of the $|S_{11}|(f)$ curve.

Based on (1) and (2), plasma conductivity is inversely proportional to collision frequency and therefore inversely proportional to n_g . As expected, when n_g is higher, the resonances observed in Figure 6 are not as sharp or deep as those observed for lower pressure scenarios. This is consistent with the modeling results obtained in [38] for an atmospheric plasma source.

4.5. Variation in the Electric Field

Another benefit of a time domain simulation of MW systems with plasma comes with an opportunity to undertake a targeted analysis of the electric field at the frequencies of particular interest. The $|S_{11}|(f)$ curves in Figures 3–6 indicate that at frequencies which are not near resonances, the level of reflections is very high and practically independent on MW power. It has been demonstrated that, in cases like that, the field distributions corresponding to $5 < P_0 < 500$ W look nearly identical, though for higher values of power, the patterns are characterized by higher magnitudes of the field [34].

Figures 7 and 8 show the patterns of the electric field for different levels of P_0 at 2.586 GHz, i.e., at the resonant frequency analyzed above (Section 4.1, Figure 3) as the one at which the energy coupling improves with the growth of power. It is seen that the increase of P_0 leads not only to the increase in the magnitude of the electric field (Tables 4 and 5), but also, through the rise in electron density of the plasma medium and its electric conductivity, to the transformation of the field distribution. Figure 7 visualizes the field in the central vertical cross-section through the system whereas Figure 8 shows the field in the horizontal cut through the lower cavity.

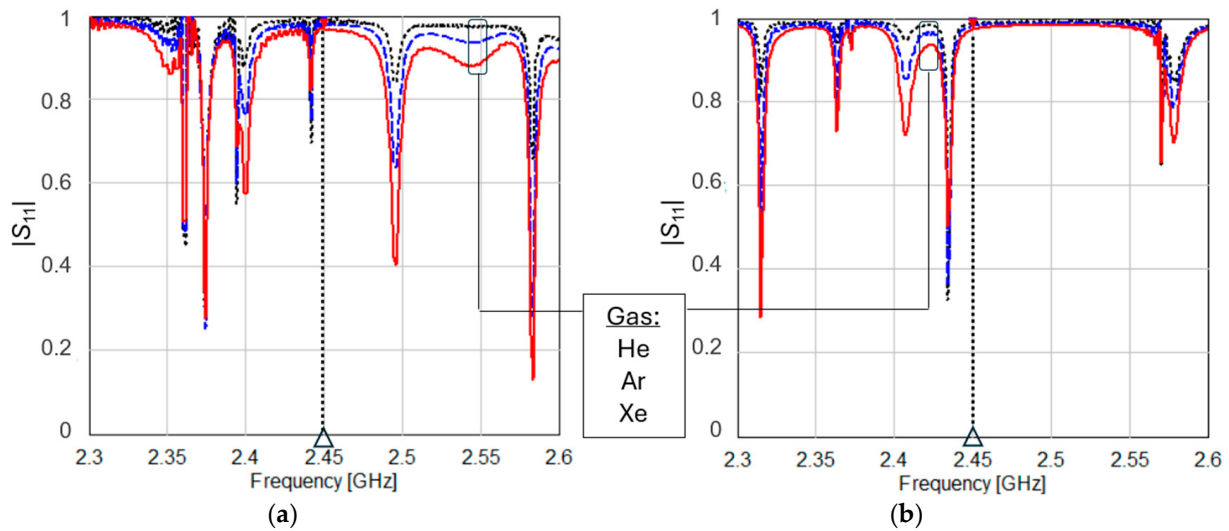


Figure 5. Frequency characteristics of the reflection coefficient in the system in Figure 1 for Helium, Argon, and Xenon; low pressure; $P_0 = 500$ W (σ by (9)); $d = 58$ mm; $p = 22$ mm (a) and 45 mm (b).

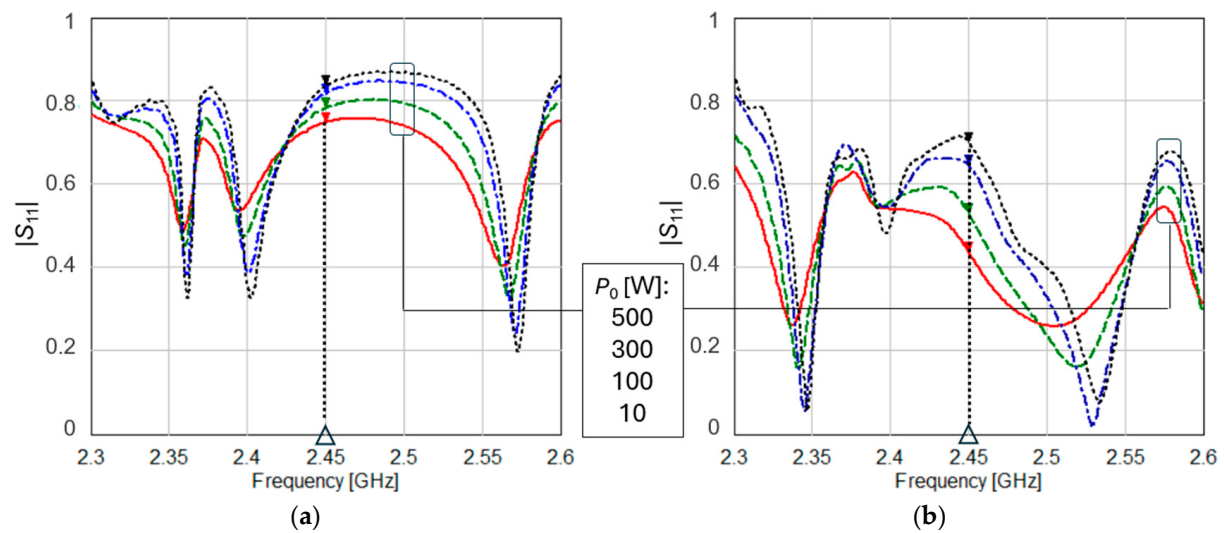


Figure 6. Frequency characteristics of the reflection coefficient in the system in Figure 1 for MW power in the range from 10 W to 500 W (σ by (9), Table 1); plasma in Argon at near atmospheric pressure; $d = 42$ mm; $p = 38$ mm (a), $d = 58$ mm; $p = 54$ mm (b).

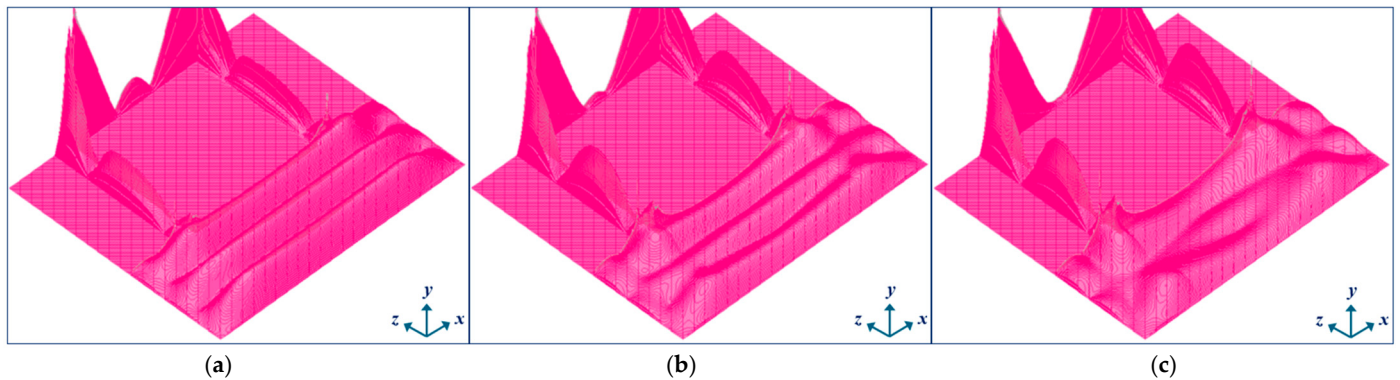


Figure 7. Surfaces of the electric field in the central yz -plane at the resonant frequency (2.586 GHz); $d = 58$ mm; $p = 54$ mm; plasma in Argon at low pressure; $P_0 = 10$ W (a), 300 W (b), 1500 W (c); σ by (9) (Table 1); maximum field values in the patterns are given in Table 4.

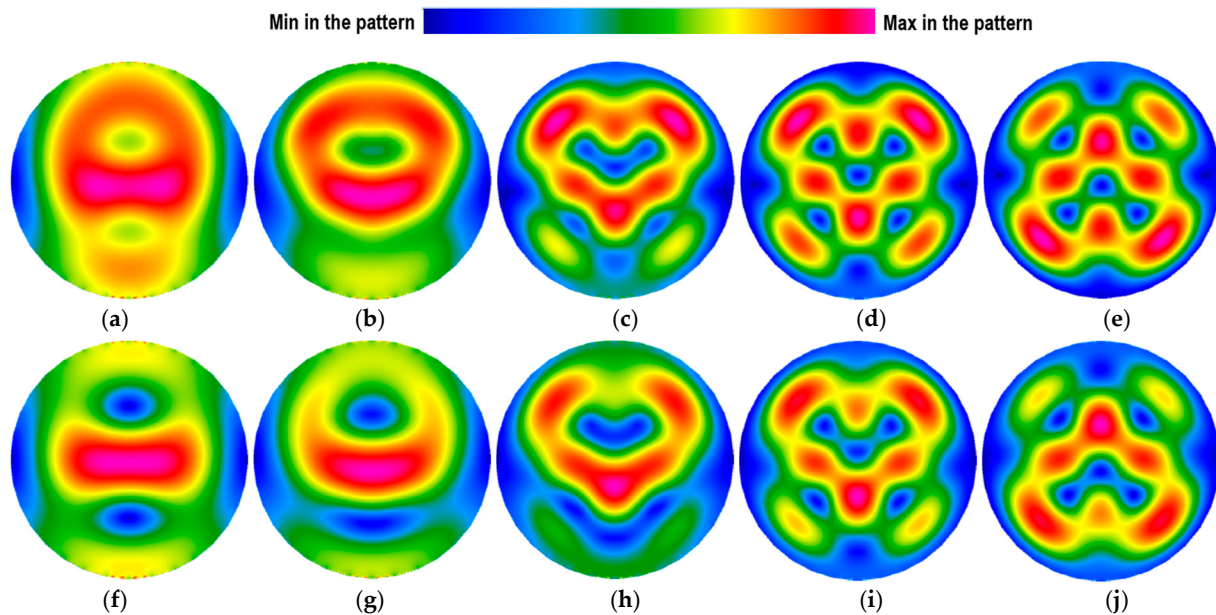


Figure 8. Thermal patterns of the electric field in the xy -plane through the lower cavity at 50 mm (a–e) and 33.5 mm (f–j) from the bottom at the resonant frequency (2.586 GHz); $d = 58$ mm; $p = 54$ mm; plasma in Argon at low pressure; $P_0 = 10$ W (a,f), 100 W (b,g), 300 W (c,h), 500 W (d,i), 1500 W (e,j); σ by (9) (Table 1); max field values in the patterns are given Table 5.

Table 4. Maximum magnitudes of the electric field in the patterns in Figure 7 and corresponding values of density of dissipated power.

Figure 7	P_0 [W]	$ E _{\max}$ [V/mm]	P_{diss} [W]
(a)	10	8.6	0.14
(b)	300	117.2	21.0
(c)	1500	431	94.4

Table 5. Maximum magnitudes of the electric field in the patterns in Figure 8.

P_0 [W]	$ E _{\max}$ [V/mm]	
	(a–e)	(f–j)
10	1.51	2.22
100	5.06	7.33
300	14.7	15.5
500	29.9	27.7
1500	71.4	67.5

A visible transformation of the field in the space around the plasma vessel is apparently conditioned by the change in plasma electric conductivity. The model also reveals a striking variation in the field distribution in the domain of its interaction with the processed material. The evolution appears to be a gradual formation of a certain mode of the cylindrical resonator (patterns (e) and (f)) that becomes possible with a sufficient level of coupling (η roughly above 50%, in accordance with Table 3) that provides “proper” excitation of the field in the cavity.

5. Discussion

The key observation from the $|S_{11}|(f)$ curves in Figures 3–6 is that for the applicator considered (Figure 2), coupling with the plasma is not merely inversely proportional to the level of MW power. The system is characterized by strong resonances, so, with the rise in P_0 , the energy efficiency of the applicator can worsen, improve, or remain permanently low, depending on whether the operating frequency P_0 is at, near, or away from a resonant frequency. In practice however, f is not a free choice, but a fixed parameter chosen to be one of the ISM frequencies. Moreover, when the dimensions of an applicator change (e.g., are increased in the framework of a scale up process), the profile of the $|S_{11}|(f)$ curves is shifted and distorted.

As a result, the output of the presented computational analysis is best interpreted following the principles of FDTD-based CAD established in microwave power engineering [30,42]. When the time-domain analysis of a given MW system produces a frequency response of the reflection coefficient possessing resonances close to f , it indicates that, with an appropriate change in geometric parameters, the $|S_{11}|(f)$ curve could be modified in such a way that the resonances occur closer to, or at, $f = 2.45$ GHz. The exact change necessary for desirable reshaping of the $|S_{11}|$ characteristics can be determined either through a series of simple computational tests, or, in more complex cases, with the use of suitable numerical optimization [43–46]. It can therefore be inferred that the analysis in Section 4 identifies feasible design variables for the optimization for the applicator considered from geometric parameters of the plasma vessel. A similar set of computations performed for other systems would similarly bring conclusions about the most impactful design variables.

From the EM perspective, a cavity enclosed by metal walls and containing a medium of high electric conductivity, like the system modeled in this paper, is a resonant structure. Accordingly, multiple resonances are exhibited in Figures 3–6. While the presented computational analysis shows that these resonant properties could potentially be used to control energy efficiency of the system and aid in industrial scaling, most of the resonances observed are sharp and narrow. As a result, tuning the resonant behavior of the system could prove challenging. It may therefore be practical to first check for design options for decreasing Q -factor for EM optimization or CAD backed by the proposed approach. Increasing the size of the plasma volume or inclusion of an “dummy load” absorbing a small part of electric energy might be considered.

On the other hand, it appears that MW systems containing plasma and intrinsically characterized by strong resonances will benefit from working with solid-state generators of MW energy that are known for fine-tuning frequency and power, i.e., for offering precise control over microwave output.

6. Conclusions

In the present paper, we have extended the simple plasma model in [32], developed for FDTD EM modeling of MW systems containing plasma, by approximating the connection between the plasma frequency (a key input parameter of an FDTD model) and MW power (a physically tunable parameter). This connection is based on a generalization of the measured data reported in the literature on electron density versus power and subsequent calculation of plasma frequency as an approximately linear function of power. The exact relationship of plasma frequency to power can be expected to be of similar nature, but the exact values of this linearity are heavily system-dependent. In this paper, we have used the equation $f_p(P_0)$ generated by data presented in [36] to produce illustrative FDTD simulations of EM characteristics in a conventional MW plasma applicator. Through this exercise, it was determined that, depending on how the operating frequency of the applicator relates to

the system's resonances, the coupling of the electric field with the plasma can decrease, increase, or remain low with the increase in power.

We have analyzed in detail the resonant conditions under which the rise in the power level leads to improved coupling and increased energy efficiency of the system. This scenario is of particular interest for CAD, assisting in efficient scaling up of systems and processes involving MW plasma because it suggests a way of mitigating the associated power limitation. In addition to this, the model has demonstrated that the variation in MW power may also result in dramatic differences in the distribution of the electric field in the cavity where the processed material would be positioned. This effect is worth further studying as a potential non-trivial mechanism of control over the field patterns.

The modeling approach introduced in [32] and expanded upon in this paper demonstrates the value of FDTD electromagnetic modeling for situations in which it is practical to simplify the plasma medium in order to understand the underlying electromagnetic processes. The proposed approach is compatible with the machine-learning procedure [46] introduced for optimization of MW plasma applicators. While the output of full multi-physics simulation can contain a large amount of data regarding the interrelated parameters of the device, it ultimately provides little clarity on the underlying processes and courses of potential action. When it comes to addressing the limitations on power for industrial scaling of MW applicators containing plasma, this approach provides simple explanations for the fundamental processes at work within these applicators and illuminates a variety of design solutions to address energy efficiency concerns.

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