Computational Analysis of Electron Density Effect on Power Absorption in Microwave Plasma Applicators

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INTRODUCTION AND METHODOLOGY

The last several years have seen an increased use of microwave (MW) plasma for hydrogen production, nitric acid synthesis, surface processing of semiconductor components, decomposition of CO_2 and other innovations [1]. When scaling up the plasma-based technologies into industrial processes, the designers inevitably face the constraint for the level of MW power. The rise in power raises electron density, which increases plasma's electric conductivity, worsening the coupling of the microwaves with the plasma, reducing power absorption, cutting the energy efficiency of the system, and limiting the potential for scalability.

In this paper, we suggest addressing this conceptual challenge by a focused computational analysis of the electromagnetic (EM) processes in the MW system in question. The recently proposed approach for the characterization of microwave plasma for EM modeling [2], [3] has laid groundwork for use of the FDTD technique to determine the operational bounds of MW applicators with plasma and assist in the CAD of such devices. To demonstrate the benefits of this approach in dealing with the electron density related challenges, we designed the model of a 2.45 GHz system resembling certain plasma applicators and simulated it using the FDTD approach, adjusting the electron density parameter to account for changes induced by the variation of MW power. The model was implemented in the FDTD simulator *QuickWave* [4]. Our computations show an anticipated increase in reflections from the system that is caused by the increase in input power. At the same time, they reveal that some alterations in the system design could take advantage of the resonant properties of the system and lead to improved coupling and increased energy efficiency.

COMPUTATIONAL RESULTS

In the considered MW device (Figure 1), the plasma is ignited in a gas enclosed in a cylindrical quartz tube positioned inside a metal cylinder connected with an exciting rectangular waveguide (whose wide wall is parallel to the y-axis) and a larger cylindrical

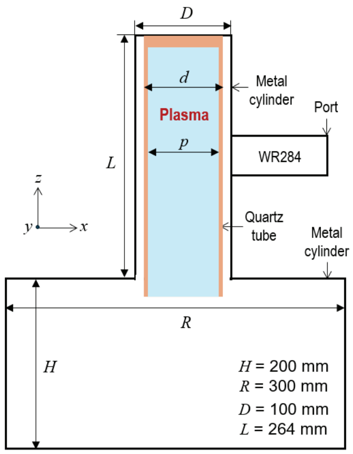
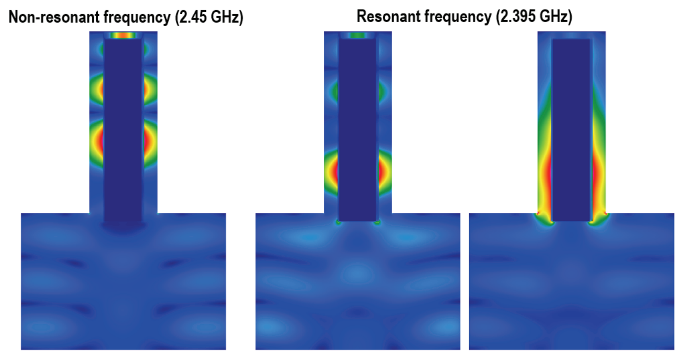


Figure 1. Layout of the microwave plasma system.



(a)

P [W]	E_{max} [V/mm]	P_{diss} [W]
10	3.05	0.57
100	9.53	4.22
300	16.6	9.02
500	21.7	12.1

(b)

P [W]	E_{max} [V/mm]	P_{diss} [W]
100	37.9	29.7

(c)

P [W]	E_{max} [V/mm]	P_{diss} [W]
500	93.3	80.2

Figure 3. Relative patterns of the electric field in the central *yz*-plane at the non-resonant (2.45 GHz) (a) and resonant (2.395 GHz) (b, c) frequencies; p = 54 mm; max values of the field and absorbed power for different P are tabulated.

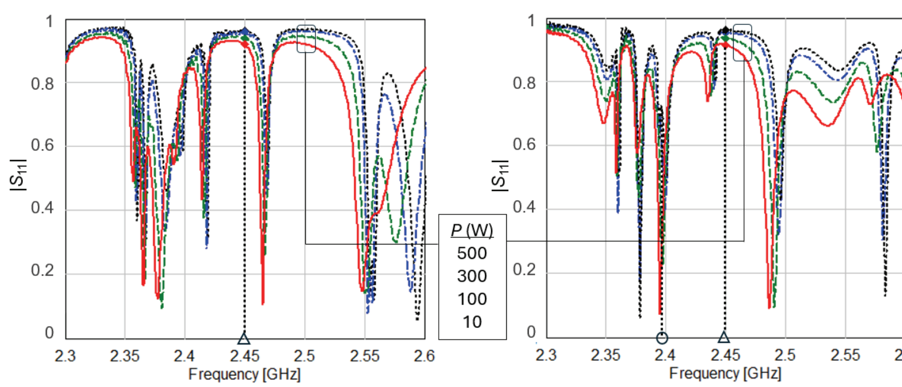


Figure 2. The reflection coefficient $|S_{11}|$ in the system in Figure 1 for MW power P in the range from 10 to 500 W; d = 58 mm; p = 38 mm (a) and 54 mm (b); plasma is ignited in argon at low pressure (with the neutral gas density $n_g = 1.94 \cdot 10^{-24}$ m^{-3} [3]); γ = 0.33 GHz [3]; non-resonant (2.45 GHz) and resonant (2.395 GHz) operating frequencies are marked by o and Δ.

cavity which serves as a reactor for the intended application. To single out the impact of plasma, the processed material is not included in the model. The input data representing the plasma medium is compiled in accordance with the approach outlined in [2], [3]. The electric conductivity of plasma σ is conditioned by electron-neutral collision frequency γ and plasma frequency f_p. The latter depends on electron density N (and can be approximated as $f_p \sim 8.97N^{-1/2}$ [3]) which is a system-specific function of MW power P. According to the experimental data in [5], [6], the dependence $N(P)$ is close to linear. Here, we define $f_p(P)$ using the slope of $N(P)$ in [5], $N \cdot 10^{-23}$ [m^{-3}] = $1.12 \cdot 10^{-3}$ P [W] + 2.57, such that then f_p [GHz] ~ 0.22 P [W] + 89.5. The increase of MW power is therefore accounted for by the growth of the plasma frequency input parameter.

Simulated frequency responses of the reflection coefficient $|S_{11}|$ obtained for different f_p (determined by MW power) (Figure 2) suggest that, in applicators similar to the device in Figure 1, the level of power absorption strongly depends on whether the operating frequency f_0 is near or at one of the resonances of the system. The curves imply that, at non-resonant frequencies, the coupling is normally very low regardless of the level of power. At a resonance, however, the decrease in energy efficiency resulting from increased electron density may be insignificant; in some cases, the coupling may even improve. The positioning of resonant frequencies depends on geometrical parameters of the system. For the system in Figure 1, the diameter of the plasma cylinder and thickness of the quartz walls are especially impactful. This suggests that the decline of energy efficiency because of increased power can be addressed instead by simply choosing a design that matches f_0 with one of the system's resonances.

As a supplementary result, the model also estimates the evolution of the electric field for the growing MW power. When P varies from 100 to 500 W, the range chosen for the present study, the resulting change in N produces an increase of σ from 111 to 323 S/m. It is seen from Figure 3 that when the system is excited at a non-resonant frequency, the absorbed (dissipated) power (P_{diss}) is very low for any level of power, and the field distributions are nearly the same. However, the field pattern may change with MW power when f_0 is tuned at a resonant frequency due to corresponding variation of plasma conductivity.

CONCLUSION

The presented computational results suggest that while the increase of electron density with the growth of MW power poses a fundamentally natural challenge, FDTD modeling of the EM processes in the considered device may inform the design such that it could help mitigate the negative effects of this phenomenon. Certain combinations of geometrical characteristics of the device and physical parameters of the plasma medium may help tune the operating frequency to the system's resonances, improve energy coupling, and increase energy efficiency for scalable MW power.

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