Characterization of Microwave Plasma in Electromagnetic Modeling for Processing Applications

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INTRODUCTION

The increasing scope of applications for microwave plasma in processing technology [1] has motivated the design of various microwave systems containing plasma. However, experimental development of efficient and controllable applicators has proven to be challenging [1]. While examples of instructive computer simulations assisting in the design of such systems are reported in [2], [3], the use of advanced modeling and CAD remains limited by a lack of clarity in how to represent microwave plasma in electromagnetic (EM) models. In this paper, we outline an approach based on the physics-driven Lorentz-Drude model, leading to an expression for the relative complex permittivity of microwave plasma. This characterization can be reduced to the electric conductivity, conditioned by the plasma frequency and the frequency of electron collisions. While the proposed approach may appear oversimplified, it allows one to infer which physical parameters of plasma are influential and to what extent. We used data obtained from this approach in an illustrative FDTD simulation of a simple microwave system containing plasma. Computational results demonstrate well-known behavior of the electric field in presence of plasma and thus suggest the legitimacy of the proposed characterization for microwave plasma in EM models.

MODEL OF COMPLEX PERMITTIVITY OF PLASMA

In physics, the Lorentz model is used to summarize the electron behavior of materials under an induced electric field [4]. It operates on the assumption that electrons are both significantly less massive than the nucleus and connected to it by a spring-like force. When an electric field is induced, the particles are polarized, and the displacement of electrons can be described using second-order differential equations for a stationary spring system. Contributions of Drude clarify the Lorentz model for metals and plasma by specifying the lack of a restorative force, a consequence of free electrons. Applying a Fourier transform to solve for electron displacement, these results can be interpreted to produce expressions for the relative complex permittivity as it is relevant to microwave plasma:

$$\varepsilon_r = \varepsilon' + i\varepsilon'' \text{ , where } \varepsilon' = 1 - \frac{\omega_p^2}{\omega^2+\gamma^2} \text{ , } \varepsilon'' = \frac{\omega_p^2 \gamma}{\omega(\omega^2+\gamma^2)} \text{ ,} \quad (1)$$

ω_p is the angular frequency of plasma, ω is the angular frequency of the EM field, and γ is the frequency of electron collisions. Referring to the Lorentz-Drude model, since the EM field frequency $f = \omega/2\pi$ is constant, microwave plasma can be characterized via the plasma frequency $f_p = \omega_p/2\pi$ and the frequency of electron collisions γ. Both these values influence the electrical conductivity $\sigma = \omega\varepsilon_o\varepsilon''$, where ε_o is the permittivity of vacuum.

The plasma frequency depends on the electron density N, which is linked to the ionization degree of the plasma, neutral gas density n_g, and the power of the microwave system P [4]. Neutral gas density changes according to the ideal gas equation, so it is influenced by both system pressure and the flow rate of gas into the plasma chamber.

The frequency of electron collisions can be defined as the product of n_g, average electron velocity v_e, and the electron collision cross section σ_{eN} [3]. An interpretation of v_e can be obtained using a Maxwell-Boltzmann distribution, given the electron temperature. It is also possible to simplify interpretations of the electron collision cross-section to a geometric representation depending on the atomic radius of the neutral gas. However, this reduction comes with certain caveats. Mainly, it does not account for the influence of charge on interactions between the free electrons and the gas molecules. This addition would imply dependence on the polarizability of the neutral gas and the electron velocity. Given the complexity of these interactions, the geometric interpretation was deemed a necessary simplification for the proposed modeling approach.

MICROWAVE PLASMA SYSTEM – MODELING OF ELECTRIC FIELD

To test how relative complex permittivity (1) represents plasma in EM simulation, we developed a model of a simple applicator resembling typical microwave plasma sources [2], [3]. The model consists of a metal cylinder and coaxially placed quartz vessel containing a neutral gas in which a plasma will be ignited. The structure is excited by a perpendicularly oriented rectangular waveguide (Figure 1). Simulations were done for WR284, D = 94 mm, d = 47 mm, L = 240 mm, l = 220 mm, and t = 1.5 mm.

Built for the 3D FDTD simulator *QuickWave* [5], the model used a non-uniform mesh with 2.0 mm cells in air and 1.5 mm cells in quartz and plasma. System performance was analyzed over a range of plasma frequencies from 0.4 to 8.0 GHz, derived from arbitrarily varied values of electron density. Additionally, the frequency of electron collisions was considered for a variety of applicable neutral gases (e.g., Helium, Argon, Xenon). In practice and in accordance with [3], this involved assigning constant values to the neutral gas density $n_g = 1.94\times10^{22}$ 1/m^3 and average electron velocity $v_e = 1.06\times10^6$ m/s. The frequency of electron collisions was then calculated with respect to values for electron collision cross-section as it is geometrically derived from the atomic radii of the given gas. The values of conductivity followed from the Lorentz-Drude model expressions (1).

System behavior was assessed with respect the relative distribution of the electric field. The set of simulated field patterns in Figure 2 clearly shows an effect of threshold of plasma frequency, where, for $f_p > f$, the electric field is reliably depicted as poorly penetrating into the plasma (enclosed in the quartz vessel).

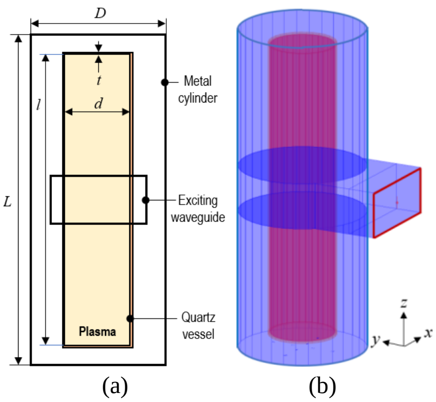

Figure 1. 2D (a) and 3D (b) views of the modeled cylindrical cavity with coaxial quartz vessel (containing plasma) and exited by a rectangular waveguide.

DISCUSSION AND CONCLUSION

In this work, characterization of microwave plasma for EM modeling is given by plasma frequency and the frequency of electron collisions. Further extrapolation of the model links these parameters to physical properties of the plasma (such as electron density, average electron velocity, the electron collision cross section) and controllable parameters of the microwave system (such as pressure and power), respectively. Dedicated experimental and theoretical studies are required to further clarify these links, however, the presented computational illustration shows correlation between the simulated field patterns and the well-known behavior of the EM field in the presence of plasma [1], [4]. This implies some legitimacy to the presented characterization route for microwave plasma.

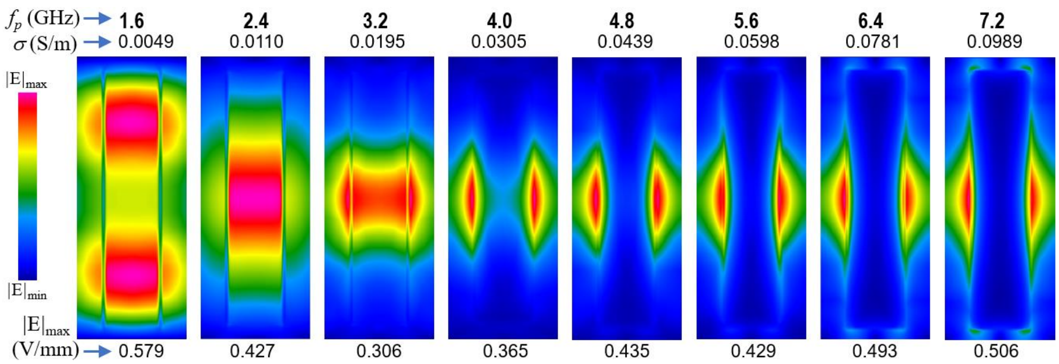

Figure 2. Relative distributions of the electric field in the central *xz*-plane of the system in Figure 1 for different values of f_p and corresponding values of σ; Argon (γ = 1.3 GHz); P = 900 W; f = 2.45 GHz; maximum values of the electric field's magnitudes |E| given for each pattern.

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