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An Optimum Electrons Number Generated in Microwaves Plasma Gas Discharge

Ahmed Salem Mohamedou*

Email: salem.saleck@gmail.com

Abstract

The objective of this study is the estimation of plasma density and the parameters that control this density in a metallic circular geometric waveguide by using microwave plasma gas discharge for plasma generation. Propagation in unlimited plasma with and without collision has been shortly treated to uncover the collision effect and the cutoff frequency. In limited plasma, in a circular waveguide, we show some waves modes that can propagate in this geometric structure. Electrons number is the main objective as it constitutes the rate of reactive species for any material treatment. Its variation with wave sources and with the dielectric constant of the tube medium has been treated.

In conclusion the design of any microwave plasma gas discharge, will be based on these parameters that are essential for guiding electromagnetic waves in a circular geometric structure for an optimum electromagnetic energy transport and as a result for an optimum reactive species rate for use in our daily life need.

Keywords: plasma; wave guides; microwaves; gas discharge; electrons number; reactive species; generation.

1. Introduction

Plasma discharge is the first and essential step in plasma treatment. By means plasma discharge we can control and estimate the type and rate of the reactive species used in the huge types of material processing.

Now days, leaders economic countries are focusing in semiconductors processing because it is the millstone for any economic unity.

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* Corresponding author.

Plasma discharge is used for the production of reactive species that control the environment pollution [4], health, space craft, material processing, treatment, ashing, dry etching and wet etching [3] It is utilized for semiconductor processing especially in making integrate circuits for microelectronic cellules. It is also used for solar cellules fabric, texture and cleaning.

In this study we will use microwaves plasma discharge for plasma generation. The objective is the estimation of plasma density and the parameters that control this density in a geometric circular waveguide. Propagation in unlimited plasma with and without collision has been shortly treated to uncover the collision effect and the cutoff frequency. In limited plasma, in a circular waveguide, we show the different waves modes that could propagate in this geometric structure. Electrons number density is the main objective as it constitutes the rate of reactive species for any material treatment. Its variation with wave sources and with the dielectric constant of the tube medium has been treated.

The design of any microwave plasma discharge will be based on these parameters that are essential for guiding electromagnetic waves in a circular geometric structure for an optimum electromagnetic energy transport and as a result for an optimum reactive species rate for use in our daily life need.

2. Propagation in unlimited plasma

For high frequency, the refractive index can be given as [1]:

$$n^2 = \chi_3, \qquad n = n_1 + in_2$$

$$\chi_3 = x_1 + i\,x_2$$

$$= \left[1 - \frac{\omega_{pe}^2}{\omega^2 + v_c^2}\right] + \left[\frac{v_c}{\omega}\frac{\omega_{pe}^2}{\omega + v_c^2}\right] \quad (1)$$

$$\left\{\begin{aligned} n_1^2 &= \frac{1}{2}\left[\left(\frac{(1-x)^2 + z^2}{1 + z^2}\right)^{1/2} + \left(1 - \frac{x}{1 + z^2}\right)\right] \\ n_2^2 &= \frac{1}{2}\left(\frac{(1-x)^2 + z^2}{1 + z^2}\right)^{1/2} - \left(1 - \frac{x}{1 + z^2}\right)\Bigg] \end{aligned}\right\} \quad (2)$$

$$x = \frac{\omega_{pe}^2}{\omega^2}, \qquad z = \frac{v_c}{\omega}$$

There is a reflection (cutoff) at $\omega = \omega_{pe}$ (x = 1), for z = 0. The propagation index square n_1^2 in equation (2), becomes negative above this frequency. **Figure.1.**

Plasma behaves as a function of its density. Electrons, ions or reactive species and neutral molecules or atoms, constitute this density. The saturation of electrons and reactive species relatively to neutral molecules and atoms may indicate the state of plasma density based on theses saturations (production of electrons and reactive species from these neutrals) for low collision frequencies.

The ratio of electrons to neutral molecules is important parameter to explain the decrease of the propagation index at the reflection, the cutoff frequency ω_p . At this frequency, plasma oscillation, the longitudinal waves can propagate but not in limited plasma. It is specific for electrons. That is why it is called electronic frequency.

For low collision frequencies, the ratio decreases shortly with the production of liberated free electrons, at a stage of plasma reservoir when the propagation index square becomes negative. The ratio of electrons to molecules increases because plasma is produced now with both their free and attached electrons. In **figure.1.a,** the transverse electromagnetic waves are the only that could propagate in the plasma above ω_p.

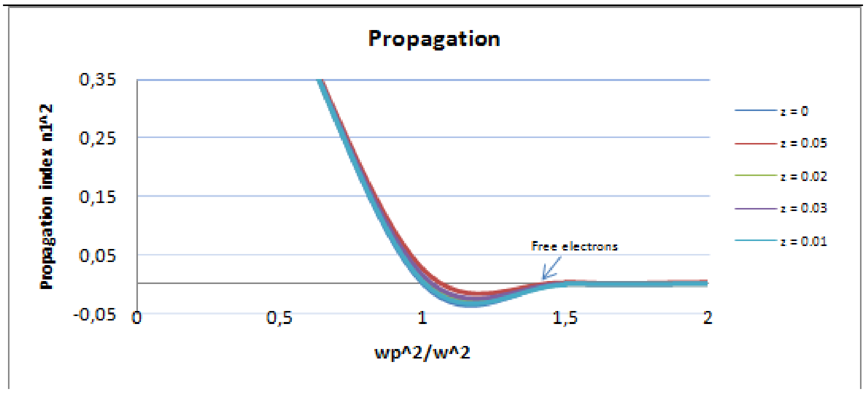

Figure 1.a: Propagation index behavior above and below plasma frequency.

For analogy, the same phenomenon happens in another natural reservoir, the saturated oil [5]. At the beginning when it was under saturated the solution gas which represents the ratio produced, decreases shortly because some of this gas is free at bubble pressure. This ratio increases and represents now both the free and the solution gas. **Figure.1.b.**

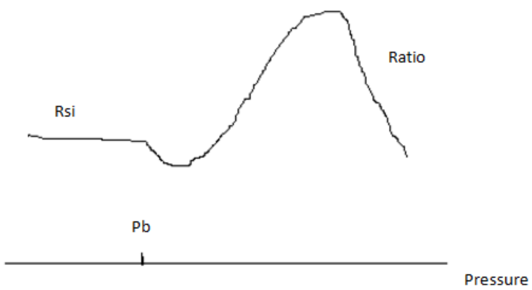

Figure 1.b: Gas ratio behavior at bubble point pressure in saturated reservoir.

These two phenomena in nature, the negative refraction index and free gas production behaviors, explain each other.

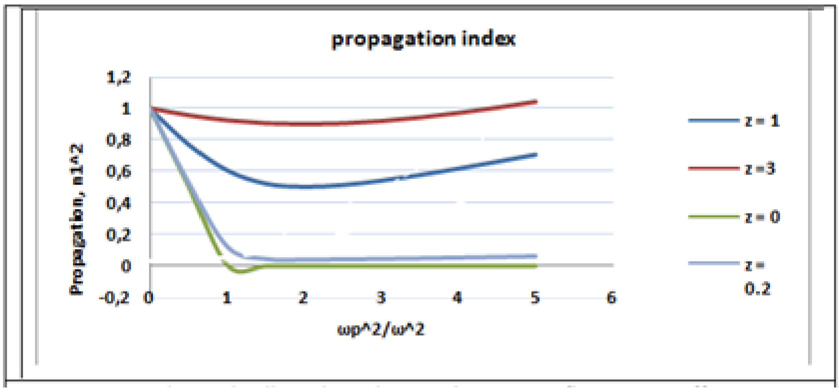

Figure 1: For unlimited collisionless plasma, there is a reflection, cutoff.

at w = wp, (x=1) for z = 0. The propagation index n1, becomes shortly negative below this frequency.

3. Propagation in limited plasma

Electromagnetic waves propagation in a circular geometric structure is governed by Maxwell's equations in that medium. The electric and magnetic component fields in these waveguides satisfy to limit conditions. There are several modes that can propagate based on the medium type that fills this geometric structure. Among these modes, there are TM and TE of respectively transverse magnetic and electric field.

For a metallic circular waveguide of 2a diameter, the longitudinal electric and magnetic field components are respectively given by equations 3 and 4 [1]:

$$\vec{E}_{//} = \vec{E}_0 J_0(S\,r) \quad (3)$$

$$\vec{H}_{//} = \vec{H}_0 J_0(S\,r) \quad (4)$$

The function J_0, is Bessel function of zero indices, solution of the Bessel differential equation. The perpendicular components in radial direction are also respectively given as function of longitudinal ones in equations 5 and 6.

$$\vec{E}_{\perp} = \frac{i\alpha}{s^2}\vec{\nabla}_{\perp}\vec{E}_{//} + \frac{i\omega}{cS^2}\vec{\nabla}_{\perp} \wedge \vec{H}_{//} \quad (5)$$

$$\vec{H}_{\perp} = \frac{i\alpha}{s^2}\vec{\nabla}_{\perp}\vec{H}_{//} - \frac{i\omega}{cS^2}\vec{\nabla}_{\perp} \wedge \vec{E}_{//} \quad (6)$$

For TM mode, the longitudinal electric field satisfies the limit condition:

$\vec{E}_{//} = \vec{0}$ at r=a;

For TE mode it satisfies:

$\vec{H}_{\perp} = \frac{i\alpha}{S^2} \vec{\nabla}_{\perp} \vec{H}_{//} = \vec{0}$ at r=a.

The graphic solutions $q_{op \text{ and } q'_{op}}$ for the two modes are respectively the solutions of $J_0(Sa)$ and $J'_0(Sa)$. Figure.2.

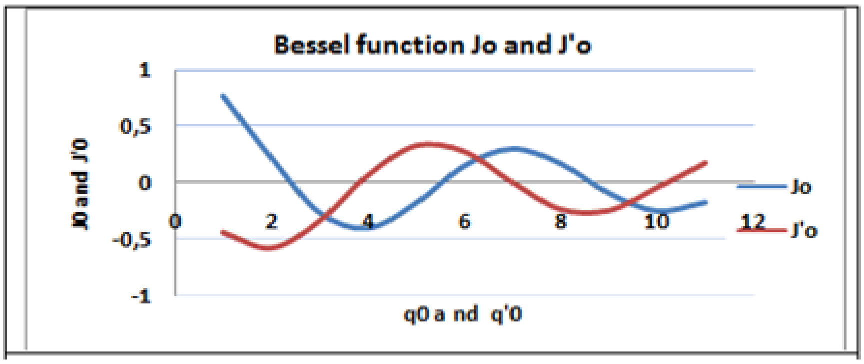

Figure 2: Bessel function and its derivative solutions, $q_{op \text{ and } q'_{op}}$, for the two circular metallic waveguide modes, TM and TE. The longitudinal magnetic field satisfy the limit condition at r = a.

4. Electrons number density

In microwaves plasma gas discharge, waves are excited in a metallic circular dielectric (glass) tube **Figure.3.** Plasma generated is a composition of electrons and reactive species. Microwaves are guided in this tube for material treatment fins. Our objective is to identify the different waveguides modes, its tendency of propagation and the electromagnetic energy path to estimate the optimum electrons number density and as a result the reactive species rate for material treatment.

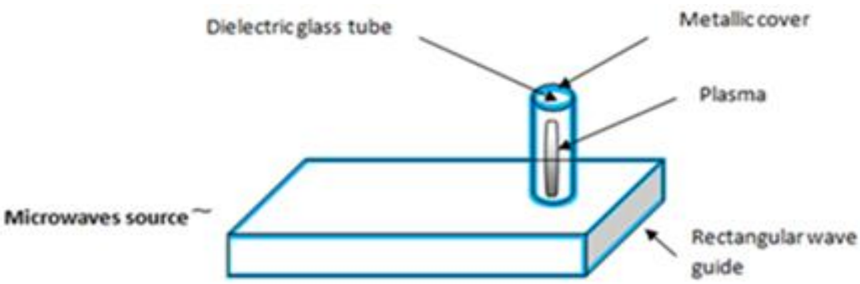

Figure 3: Microwaves plasma discharge for plasma generation. Gas inside the circular tube is excited by the rectangular waveguide [2].

For plasma discharge, tube in metallic circular geometric waveguide, waves are guided in the tube medium if the dielectric constant of the tube medium is greater than that of plasma one. The inequality (7), establish this condition:

$$1 - \frac{\omega_{pe}^2}{\omega^2 + v_c^2} < \varepsilon \quad (7),$$ where ε, is the tube medium dielectric constant.

Then $n_e < \frac{m_e(\varepsilon-1)}{4\pi q^2}\,(\omega^2 + v_c^2)$

In contrast waves will have tendency to propagate in the plasma discharge tube if

$n_e > \frac{m_e(\varepsilon-1)}{4\pi q^2}\,(\omega^2 + v_c^2)$

In general, electrons number density is function of wave source frequencies, medium dielectric and collision frequencies as in (8).

$$n_e = \frac{m_e(\varepsilon-1)}{4\pi q^2}\,(\omega^2 + v_c^2) \quad (8)$$

Electrons number density is represented in **Figure.4.** Waves guided in the tube dielectric medium will generate high electrons number density for high dielectric constant values. In this case, their electrons number is above the curve. Below the curve, waves are guided inside the tube in the plasma, and the electrons number density will be less as it seems.

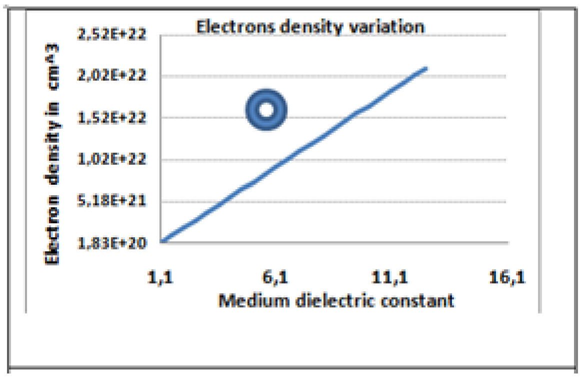

Figure 4: Waves guided inside the tube dielectric medium will generate high electrons number density for high dielectric constant. Less number density will be for waves guided inside plasma tube.

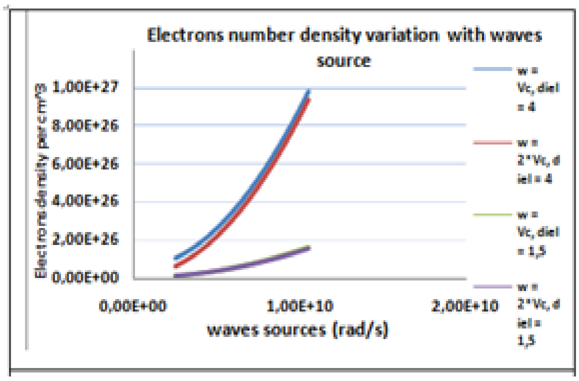

Figure 5: Electron number density increases with the tube medium dielectric constant for high waves source. The dielectric medium constant affects deeply this density.

For high waves source, the electrons number density increases with the dielectric medium constant values. The dielectric medium constant affects deeply this density. **Figure .5.**

Figures.4 and **5,** show that in guiding waves in a tube with high medium dielectric constant, electrons number will increase due to the tendency of electromagnetic waves to propagate in this medium. With high dielectric constant more electromagnetic energy will produce greater electrons number inside the tube.

By consequence, electrons number will be greater if the waves are guided in the tube dielectric medium.

For TEM mode, the dispersion relation is

$$\omega^2 = \omega_{cME}^2 + k^2c^2 \quad (9)$$

Then

$$n_{eTEM} = \frac{m_e(\varepsilon-1)}{4\pi q^2}\left(\omega_{cME}^2 + k^2c^2 + \mathrm{v}_c^2\right) \quad (10)$$

$\Rightarrow\ n_{eTEM} < n_e$, when $\omega_{cME}^2 = 0$

Cutoff frequency of TM and TE mode for limited plasma are given respectively by the relations (11) and (12).

$$\omega_{cM}^2 = \omega_{pe}^2 + \frac{q_{op}^2}{a^2}c^2 \quad (11)$$

$$\omega_{cE}^2 = \omega_{pe}^2 + \frac{q'^2_{op}}{a^2}c^2 \quad (12)$$

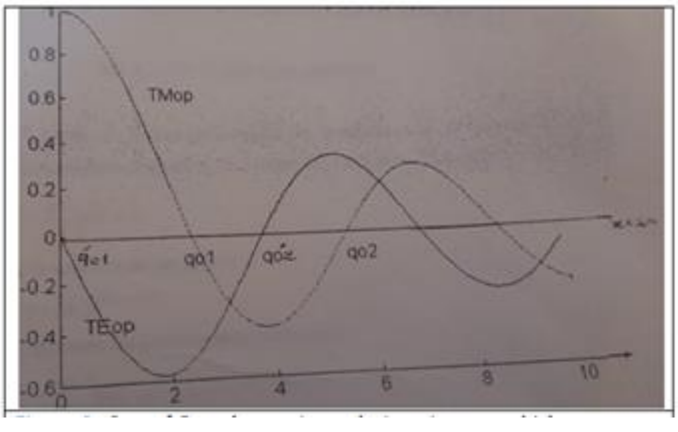

Figure 6: One of Bessel equation solutions is zero, which represents the cutoff frequency. TEM mode is clearly one of the mode that propagating in this circular waveguide. More explanations are available in the waveguide chapter treated in **the work in 1999.**

In a circular waveguide for example the coaxial two conductors, the cutoff frequency that represents one of Bessel function solutions, has a value of zero. The waveguide mode is TEM mode. In other hand, **Figure.6** shows clearly that there is a TEM mode propagating in a circular metallic waveguide. Electrons number n_{eTEM} in (10) corresponding to this mode is classified as below the curve.

The electrons number will be less in this case. The waveguide mode, the TEM mode which corresponds to lower frequency, as it seems, produce lower plasma density.

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