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Effect of Solid-State Laser Power and Gas Pressure on the Specific Fundamental Parameters of Argon DC Glow Discharge Plasma

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Abstract
This study investigates the effects of solid-state laser power and argon gas pressure on selected fundamental parameters of a DC glow discharge. The discharge was generated by applying a DC voltage of up to 6 kV, while a 532 nm solid-state laser with power ranging from 0 to 5 watts was directed through the plasma. The electron thermal de Broglie wavelength, plasma skin depth, laser phase velocity, and plasma dielectric permittivity were calculated using the electron temperature and electron density obtained in a previous experimental study. The results show that the electron thermal de Broglie wavelength increases with both laser power and gas pressure because of the corresponding reduction in electron temperature. The plasma skin depth increases approximately with gas pressure but decreases nonlinearly as the laser power increases, reflecting the associated changes in electron density and plasma conductivity. The calculated laser phase velocity decreases with increasing gas pressure and increases with laser power. In addition, the dielectric permittivity increases with gas pressure but gradually decreases as the power rises. These findings demonstrate that laser power and gas pressure can significantly influence electromagnetic-wave propagation and the fundamental properties of argon glow-discharge plasma under the investigated conditions.

Article Info.

Keywords:
DC Glow Discharge, Fundamental Plasma Parameters, Laser Power, Phase Velocity of Laser, Dielectric Permittivity of Plasma.

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1. Introduction

Due to the low breakdown voltage of argon gas and its chemical inertness, glow discharge plasma of argon and other noble gases has been used in different applications of physics such as light sources of ultraviolet radiation, new kinds of television screens, and reactors for fusion experiments, as well as the material processing of solid-to-thin-film deposition and surface modification [1]. On the other hand, experiments were carried out on laser ablation in glow discharge [2]. The experimental procedure consists of two processes: Introduction by laser ablation, which is capable of preserving the sample stoichiometry, as well as excitation of the ablated sample species by the discharge [3]. Dunaevsky et al. [4] explain the capability to produce plasma channels several millimeters in length, exhibiting satisfactory regularity, within a cylindrical gas chamber with pinholes that permit intense laser beams to directly access the plasma channel. Saini [5] investigates the optogalvanic (OG) signal in miniature neon discharge lamps. The experiments investigated laser-induced damped oscillations in the OG signal produced within the negative resistance zone of discharge plasma. The laser field behaves as a natural partner of the plasma substance. Its electromagnetic force affects the movement of the electrons and ions, which in turn leads to myriad possibilities [6]. Laser ablation was carried out by directed and focused laser pulses of high intensity into the surface of the target material. Absorption of laser energy was followed by vaporization of the sample and generation of micro-plasma [7]. Magnusson [8] investigated the interaction between the ultra-intense laser fields and the target, which rapidly ionizes and generates a plasma to sustain acceleration gradients. A diode laser SDL-475–100 T (Shanghai Dream Lasers Technology Co., Ltd.) was employed to irradiate and to excite the glow discharge (λ = 457 nm with an optical beam cross-section of 2 mm, and P = 200 mW) for laser-induced fluorescence spectra [9]. A new ambient ionization method called laser ablation micro-fabricated glow discharge plasma (LA-MFGDP) was proposed for mass spectrometry. The laser significantly enhanced the ionization capability of MFGDP in this work [10]. Ahmed [11] reports the influence of vacuum pressure and laser energy on the plasma properties induced by a Q-switched nano-laser from a titanium target. Laser-induced plasma (LIP) is one of the most suitable methods employed for obtaining plasma from solid surfaces for optical emission spectroscopic measurements. The physics of LIP indicates how the laser beam passes through the plasma and how they transfer their energy through the object. It also consists of instabilities due to the interaction of the laser with plasma waves [12].

In this paper, the interaction of a solid-state green laser of power ranging from 0 to 5 watts with argon glow discharge plasma has been taken into consideration. Furthermore, the study examines the effect and gas-pressure dependence of some fundamental plasma parameters of glow discharge generated at different gas pressures. The main research objective of the present study is to determine some specific fundamental plasma parameters, which differ from the principal parameters deduced from earlier studies, especially [13]**.** The present work is restricted to deducing the electron thermal de Broglie wavelength of electrons in plasma, plasma skin depth, laser phase velocity, and dielectric permittivity in a Maxwell–Boltzmann distribution. The determination depends on the principal parameters (electron temperature and electron density) of the previous work.

2. Experimental Part

The glow discharge system used in the present study is the same as the previous system in [13] and its picture is shown in Fig. 1. It is a cylindrical tube made from Pyrex glass that consists of two parts: the main part represents a narrow part of the tube (a discharge chamber of 0.6 cm diameter and 14 cm length). This portion of the chamber was connected in turn with two valves; one is a rotatable gas inlet, and the other is for evacuation of the system using a rotary vacuum pump, both of 1.5 cm outer diameter and 7 cm in length. The other part of the tube is a wide portion (electrode chamber of 3 cm diameter and 7 cm length). Both sides of the discharge tube were opened in order to change the distance between electrodes to obtain a stable discharge without striation at a fixed distance of 14 cm. The electrodes were mounted at the ends using vacuum rubbers of cylindrical shape, 2.8 cm in diameter and 7 cm in length. To control gas leakage. The hollow electrodes of cylindrical shape were constructed from brass metal of 0.5 cm in diameter and 9 cm in length. Brass is a field-emission electron metal and is suitable for use as electrodes in cold plasma. Before the breakdown of the gas, we have to reduce the pressure inside the chamber to the required pressure of about 1×10^{-3} mbar using a mechanical rotary pump. Then, let pure argon gas enter the system via a needle valve; repeat the step three times to ensure that the gas inside the chamber is pure argon gas at a certain pressure by using a thermocouple vacuum gauge. A high-voltage DC power supply in the range of up to 6kV is required for ignition of the discharge at different argon gas pressures, as shown in Fig. 1. The 5-watt green diode laser is directed to the anode of the discharge tube. For alignment of the laser, four vertical mirrors are used to raise the laser light from a height of 5 to 23 cm and to easily direct it to the discharge as well as to focus on the anode plasma tube. This, in turn, passes through a glass window to the plasma discharge and is reflected to the other side by another mirror fixed at the surface of the cathode.

3. Results and Discussion

This work explores the combined effects of a laser power of 5 watts and the pressure on the behavior of fundamental plasma parameters. For further explanation of the role of the laser power in the excitation and ionization of plasma particles, as well as the absorption and penetration of the laser beam inside the discharge. Determination of some fundamental plasma parameters has been done under the effects of laser power and pressure, which is in turn dependent on the experimental results of the previous work [13].

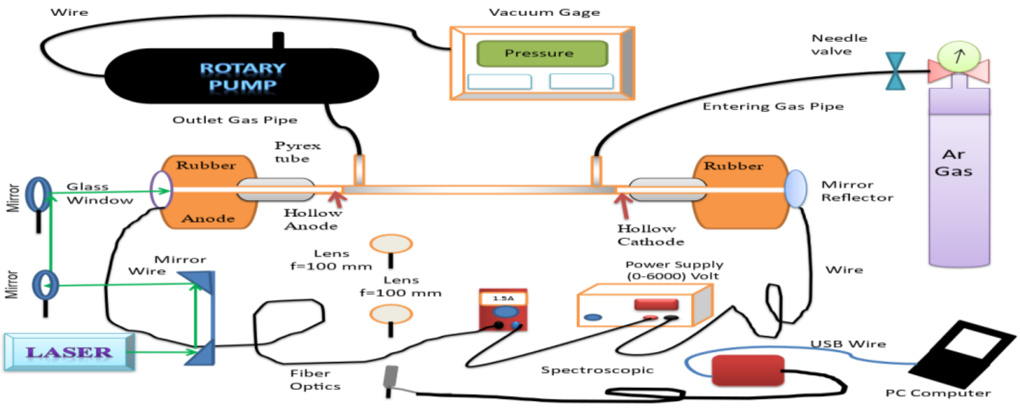

Figure 1: Diagram of the system with a laser beam traversing a discharge.

Electron thermal de-Broglie wavelength, which is roughly equal to the mean value of the de-Broglie wavelength of electrons inside the discharge, can be deduced according to the following equation [14]:

$$\lambda_{th,e} = \left(\frac{h^2}{2\pi m_e k T_e}\right)^{1/2} \approx 6.919 \times 10^{-8} \frac{1}{(T_e)^{1/2}} \text{ cm} \qquad (1)$$

$\lambda_{th,e}$= Electron thermal de Broglie wavelength in (cm), H = Planck's constant 6.626×10^{-34} J·s, m_e = Electron mass 9.11×10^{-31} kg, k = Boltzmann constant 1.38×10^{-23} J/K, and T_e = Electron temperature eV.

Fig. 2 illustrates the electron thermal de Broglie wavelength pressure dependence. The image indicates that the behavior is almost exponentially growing, as shown by the equation of fitting. This is attributed to the fact that increasing gas pressure leads to decreasing electron temperature due to the collision of electrons with other plasma particles. Therefore, the electron thermal de-Broglie wavelength increases according to Eq. (1). However, Fig. 3 plots the electron thermal de-Broglie wavelength variation with the solid-state laser power up to 5 watts.

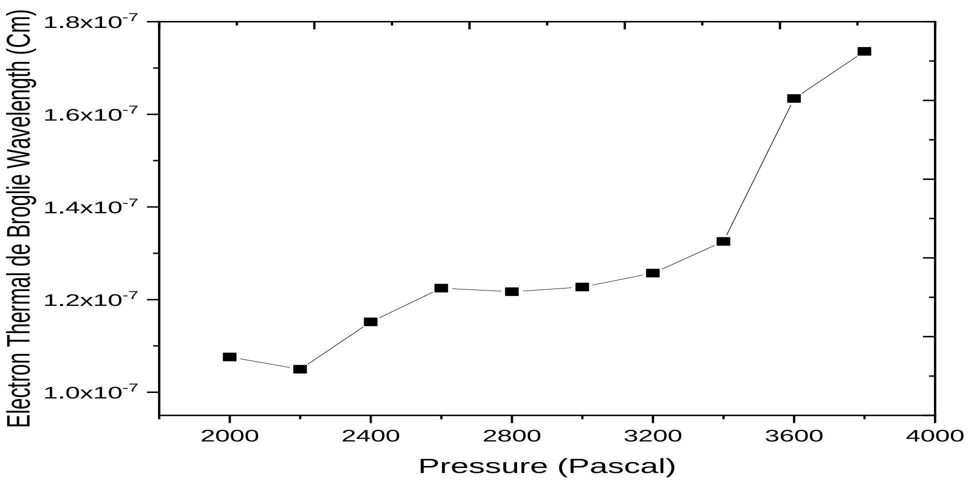

Figure 2: Electron thermal de-Broglie wavelength versus gas pressure.

Fig. 3 is roughly similar to an increasing exponential function according to the fitting of the curve. Increasing laser power causes a decrease in electron temperature [13]. It can be deduced that certain molecules can acquire energy above the binding energy when high-intensity laser radiation causes laser-induced breakdown (LIB) in a gas. Additionally, some of their electrons get so powerful that they ionize molecules and atoms. At these high temperatures, the gas transforms into a mixture of primary molecules, ions, first- and second-ionized atoms, as in the case of electrons and oxygen molecules (O2, O, O+, O2+). These processes enhance the number of collisions between the particles, leading to a decrease in electron temperature. Since the electron will lose most of their energy during the collisions. Another remarkable plasma parameter is skin depth; in other words, the depth of penetration of the wave in the discharge, which is very important because this parameter is related to the mechanism of heating in the plasma state and its conductivity. Eq. (2) determines the plasma skin depth δ_P, which is solely dependent on the plasma density [15].

$$\delta_p = \frac{c}{\omega_{pe}} \approx 5.31 \times 10^5 \frac{1}{(n_e)^{1/2}} \quad (cm) \tag{2}$$

where c is the velocity of light, ω_{pe} is the electron plasma frequency, n_e is electron density.

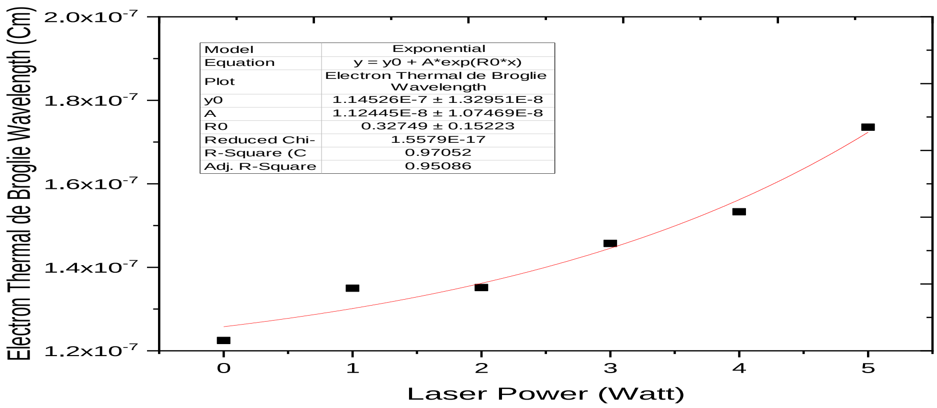

Figure 3: Electron thermal de-Broglie wavelength versus laser power.

Fig. 4 shows the pressure dependence of skin depth. The penetration depth rises as gas pressure does, as seen in Figure (4). The relation $\delta_p = \frac{1}{(n_e)^{1/2}}$ in equation (2) indicates that the effective electron density falls as the gas pressure rises. The improve of non-ionizing collisions (such as elastic and excitation collisions), which restrict ionization efficiency and lower the quantity of free electrons, is responsible for this decrease. As a result, the electromagnetic wave enters the plasma more deeply. Therefore, the skin depth of penetration increases since this parameter increases as the conductivity of the conductor decreases [16].

The influence of the laser beam on the argon glow discharge occurs through absorption and heating of plasma particles; this, in turn, increases the kinetic energy of these particles. This is followed by further ionizing collisions between them, leading to a decrease in temperature because the electrons lose most of their energy during these collisions. This increases the electron density in the plasma. Consequently, the plasma conductivity increases, decreasing the skin depth penetration into the plasma nearly exponentially with laser power. Fig. 5 illustrates this variation of plasma skin depth with the green laser power up to 5 watts.

The most important parameter that depends directly on the plasma frequency and the laser wave propagation in plasmas is the phase velocity of the laser.

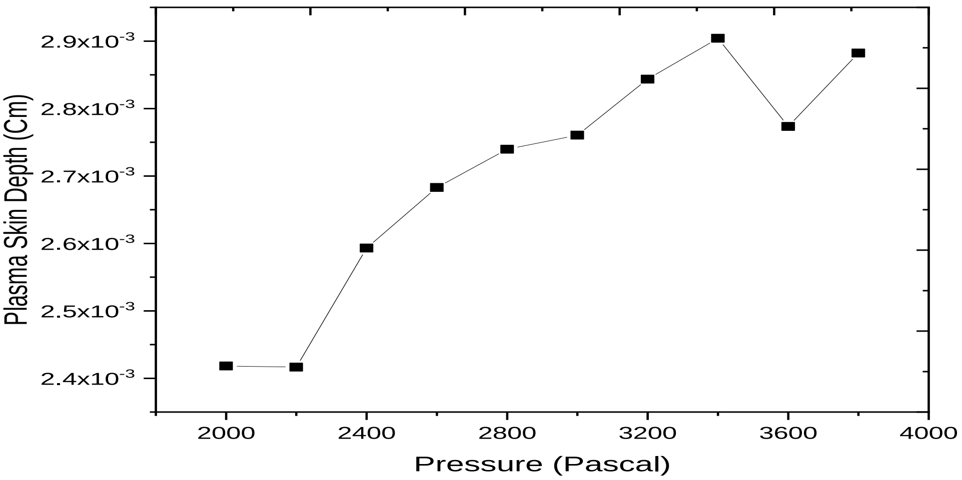

Figure 4: Plasma skin depth versus plasma pressure.

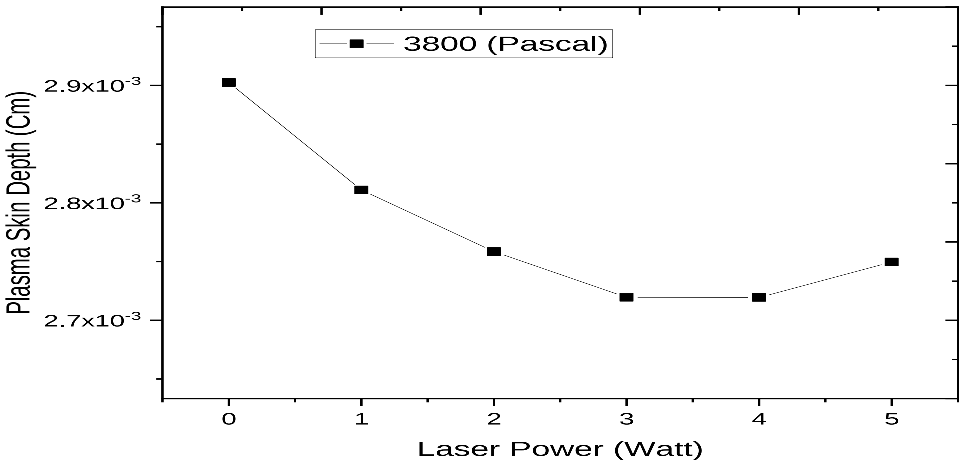

Figure 5: Illustration of the variation of skin depth with laser power.

This parameter can be given for under-dense plasmas ($n_e << n_c$), where n_e is the electron density and n_c is the critical density of plasma, given as follows:

$$n_e = 10^{21} (\lambda_L)^{-2} \, cm^{-3} \quad (3)$$

with λ_L = laser wavelength = 532 nm, and this value changes according to the change. The phase velocity is given by the following equation [17]:

$$V_p = \frac{\omega}{k} \approx c\left(1 + \frac{{\omega_p}^2}{2\omega^2}\right) \quad (4)$$

where ω_p is the angular frequency of the plasma, and ω is the angular frequency of the laser.

Eq. (4) shows that the phase velocity of a laser is always greater than the light velocity for both plasma frequencies less than and larger than the laser frequency. The phase velocity of the laser changes inversely with gas pressure, as shown in Fig. 6.

Since increasing gas pressure reduces the electron density and consequently the plasma frequency [18]. Therefore, phase velocity decreases as illustrated in Eq. (3). On the other hand, the phase velocity of the laser in plasma varies with laser power close to linear behavior, as represented in Fig. 7. This variation is attributed to the fact that enhancing laser power produces more electron density due to ionization collisions. This effect later increases the plasma frequency as well as the phase velocity of the laser in plasma.

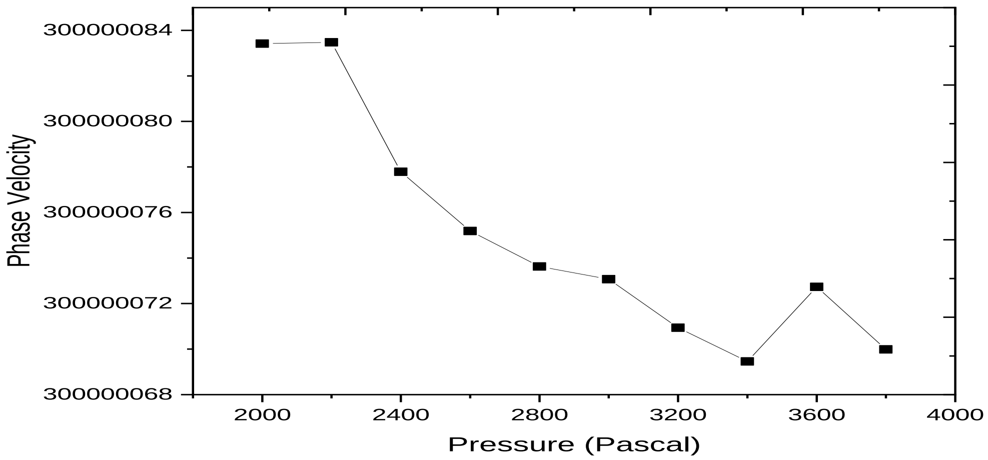

Figure 6: Phase velocity of the laser in plasma against the gas pressures.

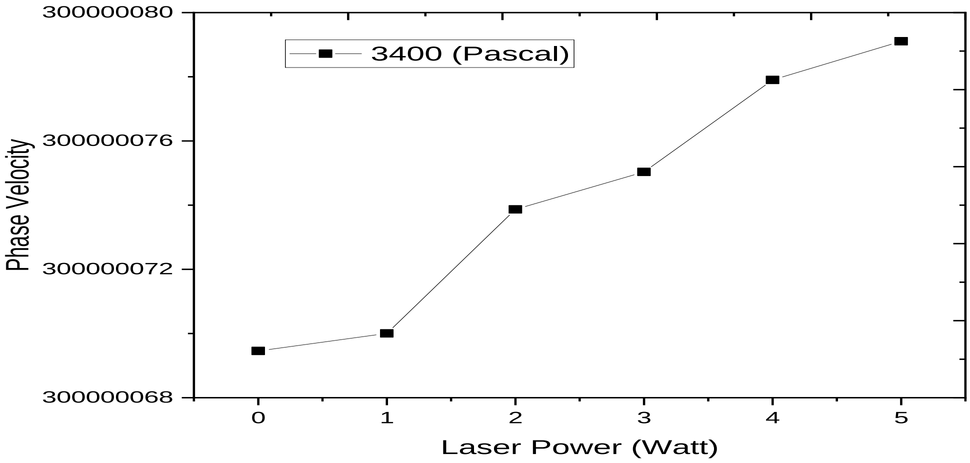

Figure 7: Phase velocity of the laser in plasma against the laser power.

Further investigation is needed to determine the effect of gas pressure and laser power up to 5 watts on some important plasma parameters such as the dielectric constant. We restrict our attention to the glow discharge substance that essentially behaves like a dielectric medium with the dielectric permittivity ϵ given by Eq. (5):

$$\epsilon = \left(1 - \frac{{\omega_{pe}}^2}{\omega^2}\right) \quad (\mathbf{5})$$

In cases of frequencies larger than the glow discharge frequency, the dielectric permittivity of a discharge is less than unity. This indicates that when the electromagnetic frequency is larger than the plasma frequency, the wave (laser) can pass across the discharge with a velocity quicker than the velocity of light in free space [19, 20].

Fig. 8 illustrates that the dielectric permittivity increases with increasing pressure, which in turn decreases both the electron temperature and its density. Hence, the dielectric permittivity of the discharge increases. This means that the conductivity of the discharge decreases due to the decrease in the number of charge carriers. However, the effect of laser power on dielectric permittivity is illustrated in Fig. 9. The figure indicates that the dielectric constant varies inversely with the laser power, since increasing laser power will enhance electron density as well as plasma frequency. This latter process reduces the dielectric constant due to increasing plasma electrical conductivity.

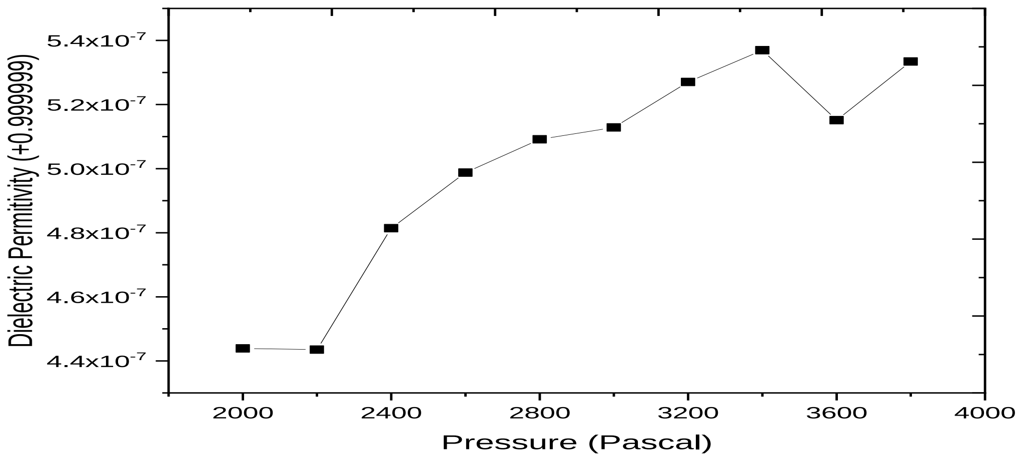

Figure 8: Plasma dielectric permittivity versus pressure.

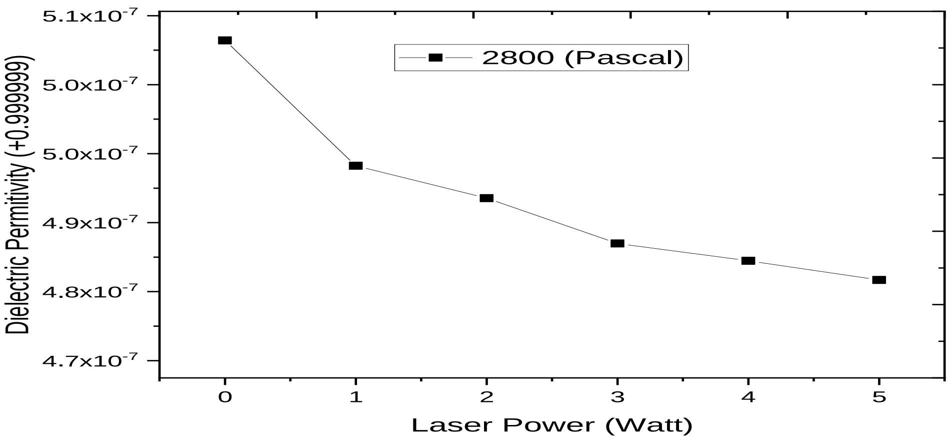

Figure 9: Plasma dielectric constant against laser power.

4. Conclusions

Several properties of the glow discharge plasma's argon abnormal region have been determined under various laser power and pressure settings, ranging from 0 to 5 watts. This type of discharge has characteristics of linear variation of discharge current according to the applied voltage (positive resistance). The calculated parameters appeared to show a remarkable change in laser power and pressure. The electron thermal de-Broglie wavelength increases from 1.2 to 1.7 × 10^{-7} cm according to the enhancement of both pressure and laser power due to non-ionizing collisions between plasma particles. Plasma skin depth also increases approximately from 2.4 to 2.9 × 10^{-3} cm as the gas pressure is raised from 2.3 to 3.5 × 10^{-2} mbar, while it decreases due to increasing laser power. The phase velocity of the laser in plasma changes inversely with gas pressure because of encounters with other plasma particles that do not ionize. However, this parameter varies nearly linearly with increasing laser power. Finally, plasma dielectric permittivity also increases nearly linearly from 0.44 to 0.5 due to rising pressure, which reduces both electron temperature and its density. This means that the electrical conductivity of the discharge decreases accordingly. With respect to the influence of laser power on the dielectric constant, the variation follows a falling curve.

Conflict of Interest

The authors declare that they have no conflict of interest.

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تاثير قدرة ليزر الحالة الصلبة و ضغط العاز على المتغيرات الاساسية النوعية لبلازما النفريغ التوهجي لغاز الاركون

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الخلاصة

تدرس هذه الدراسة تأثير قدرة ليزر الحالة الصلبة وضغط غاز الأرجون على بعض المعايير الأساسية لتفريغ التوهج المستمر. تم توليد التفريغ بتطبيق جهد مستمر يصل إلى 6 كيلوفولت، مع توجيه ليزر الحالة الصلبة بطول موجي 532 نانومتر وقدرات تتراوح من 0 إلى 5 واط عبر البلازما. تم حساب طول موجة دي برولي الحرارية للإلكترونات، وعمق اختراق البلازما، وسرعة طور الليزر، وثابت عزل البلازما باستخدام درجة حرارة الإلكترونات وكثافتها المُستمدة من دراسة تجريبية سابقة. تُظهر النتائج أن طول موجة دي برولي الحرارية للإلكترونات يزداد مع كل من قدرة الليزر وضغط الغاز نتيجةً لانخفاض درجة حرارة الإلكترونات. يزداد عمق اختراق البلازما تقريبًا مع ضغط الغاز، ولكنه يتناقص بشكل غير خطي مع زيادة قدرة الليزر، مما يعكس التغيرات المصاحبة في كثافة الإلكترونات وموصلية البلازما. تتناقص سرعة طور الليزر المحسوبة مع زيادة ضغط الغاز، وتزداد مع زيادة قدرة الليزر. بالإضافة إلى ذلك، يزداد ثابت العزل مع ضغط الغاز، ولكنه يتناقص تدريجيًا مع ارتفاع القدرة. توضح هذه النتائج أن قوة الليزر وضغط الغاز يمكن أن يؤثرا بشكل كبير على انتشار الموجات الكهرومغناطيسية والخصائص الأساسية لبلازما تفريغ التوهج الأرجون في ظل الظروف التي تم فحصها.

الكلمات المفتاحيه: التفريغ التوجهي المستمر، المتغيرات الاساسية للبلازما، قدرة الليزر، سرعة طور الليزر، سماحية البلازما.