

New Spectral Range Generations from Laser-plasma Interaction

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Abstract:

High-intensity laser-produced plasma has been extensively investigated in many studies. In this demonstration, a new spectral range was observed in the resulted spectra from the laser-plasma interaction, which opens up new discussions for new light source generation. Moreover, the characterizations of plasma have been improved through the interaction process of laser-plasma. Three types of laser were incorporated in the measurements, continuous-wave CW He-Ne laser, CW diode green laser, pulse Nd: YAG laser. As the plasma system, DC glow discharge plasma under the vacuum chamber was considered in this research. The plasma spectral peaks were evaluated, where they refer to Nitrogen gas. The results indicated that the plasma intensity increased from several thousands to several tens of thousands through the process of interaction of the Nd: YAG laser with the plasma. This increase in the intensity of the plasma as laser intensity increased occurs regardless of laser wavelength involved in the interaction or not. According to laser-plasma interaction, the so-called full width at half maximum FWHM of the highest peak in the plasma spectrum was broadened from 1.43 to 2.73. Considering the equation of plasma density computing, the plasma density was increased from 1.07×10^{18} to $2.05 \times 10^{18} \text{ cm}^{-3}$ with increasing FWHM. As a result of the interaction, the electron temperature of plasma was increased from 0.176 to 0.782 eV. It was also noticed that the position of the highest peak in the plasma spectrum depends on the interacted laser wavelength.

Keywords: CW laser, DC glow discharge plasma, High brightness light, Laser-Plasma interaction, Pulse laser sources.

Introduction:

High-intensity laser-produced plasma has been extensively investigated as a method for artificial plasma generating (1- 3). The usage of high-intensity laser-produced plasmas for particle acceleration has grabbed attention in recent years because they have been offering a compact and low cost of relativistic electron Beams. However, such a complex interaction between high-intensity short pulses of laser and plasmas is still not well understood, therefore the amount of investigation remains to understand completely the electron acceleration processes (4). In this paper, the basic concepts on the interaction of laser light with the plasma, and the enhancement of plasma characterization are investigated. This study can present an important attempt for the understanding

of the recently laser-plasma experiments. Additionally, the results presented here could find applications in the fundamental theory of intense light propagation through plasma. The interaction between the laser radiation and free electrons of the plasma was described by the Drude model by taking into account the electron motion in the laser field as a harmonic oscillator (5). Three types of motion inside the disturbed plasma by laser could be distinguished producing three types of population in the plasma electron spectrum. One is the motion inside the electrostatic oscillation body, the second belongs to the electrons which are produced in the wave-break, the third exchanges energy with plasma oscillations (6). Recent investigation has suggested that the plasma electrons could be

accelerated directly by the laser fields, where the energy transfers from the laser beam into the generated plasma, and the acceleration speed depends on laser intensities (7). The laser energy can almost deposit in the plasma and fast electrons, this energy transfers into wakefields and can be moved to ions during the process of plasma channeling (8). All these processes are typical features of relativistic interactions. However, in laser-plasma interactions, the electric field plays a major role in defining the properties of the generated plasma. When the laser electric field is propagating into the plasma, part of it is reflecting, and the other is absorbed depending on the frequencies of both laser and plasma (8). Laser electric field amplitude and its frequency are given by (8):

$$E_L (V/cm) = 2.75 \times 10^9 \left(\frac{I_L}{10^{16} W/cm^2} \right)^{1/2} \quad \dots 1$$

$$\omega_L (S^{-1}) = \frac{2\pi c}{\lambda_L} = 1.88 \times 10^{15} \left(\frac{\mu m}{\lambda_L} \right) \quad \dots 2$$

Where I_L is the laser energy flux, λ_L is the laser wavelength and ω_L is the laser frequency. The ratio of $\frac{2\pi c}{\lambda_L}$ is corresponding to one laser oscillation.

By taking into account the associated magnetic field, then the laser magnetic field amplitude is given by (8):

$$B_L (Gauss) = 2.9 \times 10^6 \left(\frac{I_L}{10^{16} W/cm^2} \right)^{1/2} \quad \dots 3$$

Where the parameters were defined above and the related frequency was given in Eq. 2.

At a limited incident angle of laser with plasma and specific plasma density, the scattering process could be occurred corresponding to Raman scattering, which results in the wave vector non-

alignment between the main laser pulse and the produced plasma wave (9,10).

In our research, new light sources generations based on the interaction of laser-plasma was investigated, in addition to the plasma characterization enhancement. Where High brightness light sources present as an attractive source in many applications, for instance: power stability repeatable light sources, sources for measurements of the illumination in a lithography system which are used in the fabrication of wafers, a photoresist curing system, a microscopy system, light source for spectroscopy applications. Owing to the mentioned applications, such a light source becomes important to generate high brightness light sources and this is the aim of this work.

Materials and Method:

The schematic of the experimental setup is shown in Fig. 1, which includes the plasma system, laser light source, spectrometer, PC for spectra recording, and data analysis. The DC plasma glow discharge consists of high voltage power supply, two electrodes separated about 4 to 5 mm inside the vacuum chamber. The electrical potential needs to be high enough (hundreds to thousands of Volts) to breakdown the gas into a plasma, here 5 kV was taken from the power supply. The plasma system has a vacuum pump, an inlet valve system, and a pressure sensor. The gap between the two electrodes is filled with air, the electric field in the gap has to be high enough to initiate an electrical breakdown in the gap. The distance between the two electrodes must be efficiently adjusted to generate plasma emission.

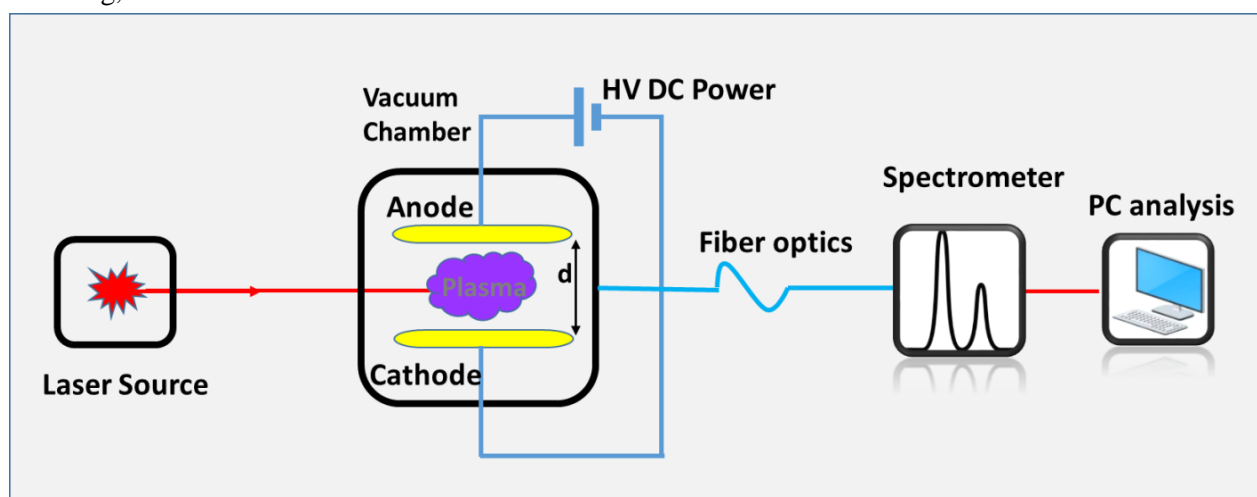


Figure 1. The Scheme of the Lab setup for the investigation of Laser-Plasma interaction.

In order to evaluate the results from the interaction of plasma and laser, three laser light sources were involved in this investigation. Two lasers are operating with continuous-wave CW, 1

mW Helium-Neon laser $\lambda=650$ nm, and Diode laser $\lambda=530$ nm with an output power of 2 mW. The third one is Nd:YAG pulsed laser with $\lambda=1064$ nm, maximum pulse energy of 750 mJ, a repetition rate

of 10 Hz, and a pulse width of 9 ns. A spectrometer with ICCD rays from surwit (S3000-UV-NIR) was adopted for spectra recording.

Results and Discussion:

In this paper, a novel measurement method of laser-plasma interaction has been presented. All measurements were performed at room temperature. Figure 2 shows the plasma spectrum measured using a spectrometer. The peaks that appeared in the

plasma spectrum were performed by comparing the wavelengths recorded with the National Institute of Standards and Technology NIST data, and they were shown belong to nitrogen gas (has a high concentration in the atmosphere). Besides, the plasma spectrum shown in Fig. 2 has good agreement with (11,12) from the peak positions and spectral range of N₂.

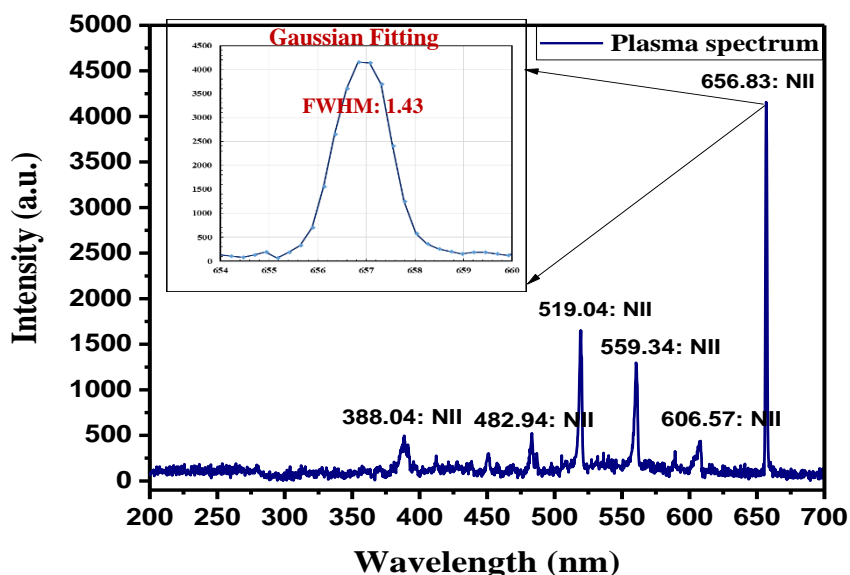


Figure 2. The plasma spectrum including Gaussian fitting of the highest peak.

Gaussian fitting of the highest peak appearing in the plasma spectrum (see Fig. 2) is important for calculating the electron density N_e by determining the full width at half the maximum FWHM of this peak. Taking into account the peak-related parameters, which can be determined from the NIST data, both the electron density N_e in the unit of cm⁻³ and electron temperature T_e in eV unite, can be calculated. The equation that governs N_e (10, 13) is given in the formula as in:

$$N_e = \left(\frac{\Delta\lambda}{2\omega} \right) \times 10^{16} \quad \dots 4$$

Where $\Delta\lambda$ is the FWHM explained above. ω is the frequency at $\Delta\lambda$.

After plasma initiating and moving to the stabilization regimes, the lasers were focused separately and sequentially on the generated

plasma. The ideal waist diameter of a Laser Gaussian beam was focused by an optical lens used in this work. Then the spectra were recorded, analyzed, and evaluated as a result of the interaction of each laser with the plasma. After that, the plasma electron density and electron temperature were calculated.

Figure 3 shows the measured spectra from the laser-plasma interaction. Where **a** shows the measured spectrum from the interaction of plasma and He-Ne laser, while **b** and **c** present the collected spectra from the interaction of plasma with diode green laser and Nd:YAG laser, respectively. The labeled wavelength belongs to each peak has been described in **a**, **b**, **c**, denote to N₂ by matching each peak wavelength with the NIST spectra (14).

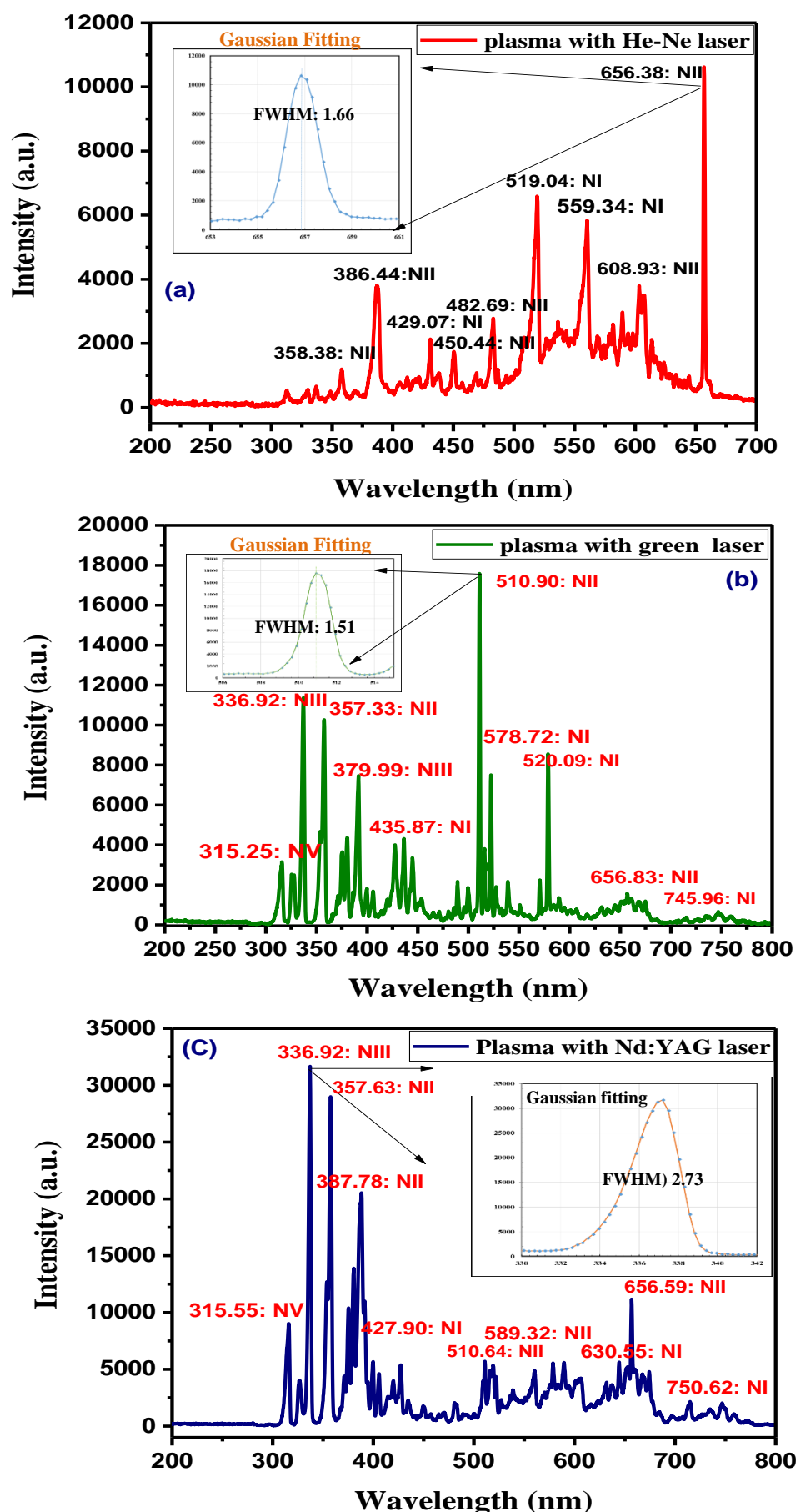


Figure 3. The plasma- laser interaction spectra including Gaussian fitting of the highest peak., a) -He-Ne laser-plasma, b) - diode green laser-plasma, c) Nd:YAG laser-plasma.

Gaussian fitting was analyzed for the highest peak appeared in the spectra to calculate each of Ne. as clarified above. The broadening in the FWHM is according to the collision of charged species. Where the local electric field created by plasma causes spectral line splitting. This phenomenon, known as the Stark effect, is influencing these emission spectra causing line broadening (13).

To calculate the electron temperature T_e , Boltzmann distribution can be used as an approximation to determine it (10, 13) as follows:

$$\ln\left(\frac{\lambda I}{hcAg}\right) = -\frac{E}{kT} + \ln\left(\frac{N}{T_e}\right) \quad \dots 5$$

Where I is the laser intensity, kT are Boltzmann constant and the temperature. $A g$ are the transition probabilities and statistical weight of ground-state

level (both are taken from NIST data). h is the Planck's constant. N and E are the total number density of emitting atoms and energy transitions involved in the measurements in the unit of eV. The plasma electron density N_e can be calculated from Eq. 4, while the electron temperature computes from Eq. 5. Plotting $\ln\left(\frac{\lambda I}{hcAg}\right)$ vs E for the known lines appeared in the measured spectra (Boltzmann plot), the resulted straight lines (Fig. 4) would have a slope of $-\frac{1}{kT}$. Therefore, the electron temperature can be obtained without taking into consideration the total number density of atoms N . Table 1 shows the summary of the plasma characterizations of the electron density N_e and the electron temperature T_e according to the presented results in Figs. 3 and 4.

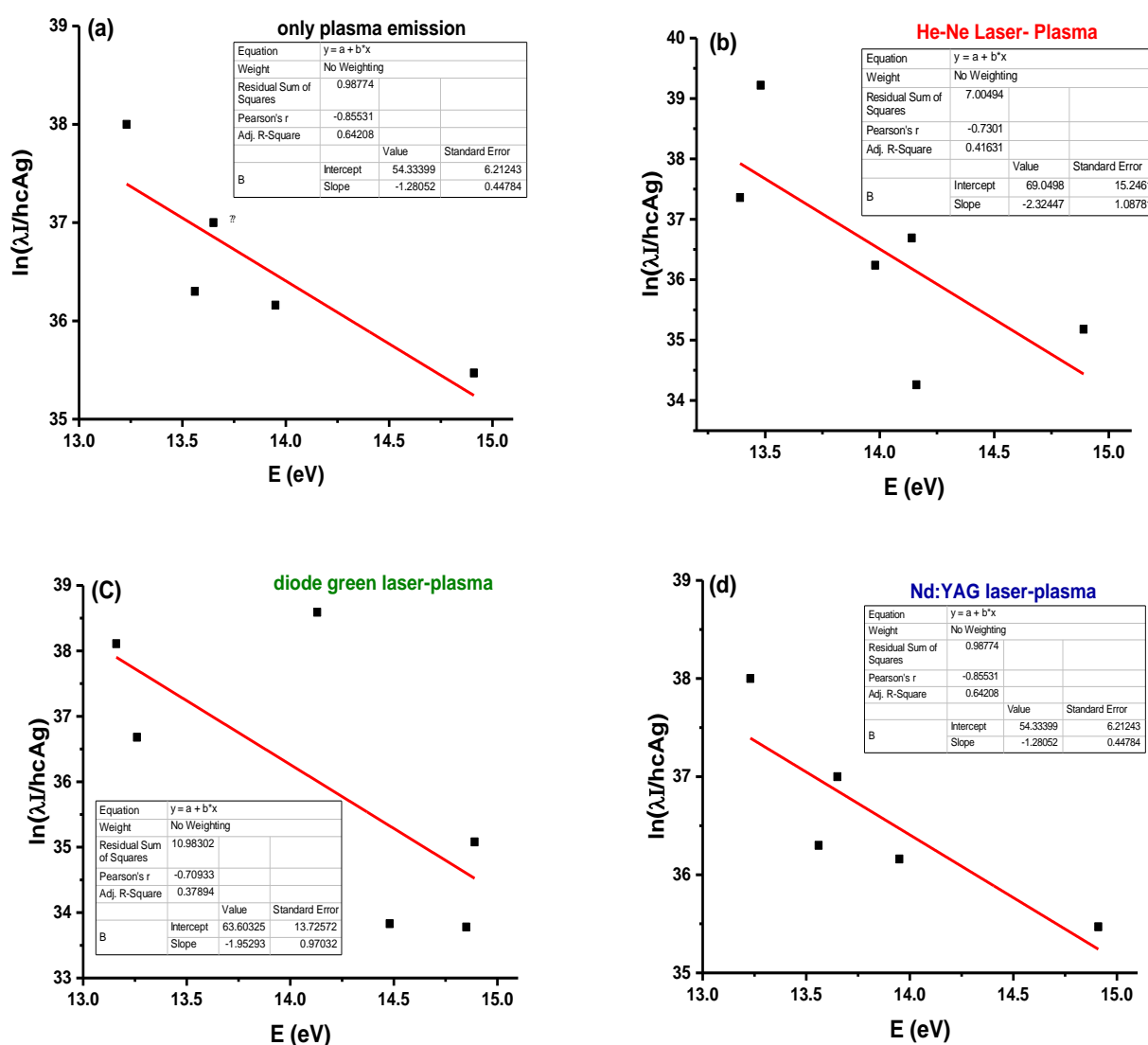


Figure 4. Boltzmann plot for N_2 spectral lines a) only plasma emission, b) He-Ne laser-plasma, c) diode green laser-plasma, d) Nd:YAG laser-plasma.

Table 1. Electron density N_e and electron temperature T_e of DC glow discharge plasma, in addition to the enhancement obtained from the interaction different laser wavelengths.

Variables	FWHM	$N_e \times 10^{18} (\text{cm}^{-3})$	$T_e (\text{eV})$
Only plasma	1.43	1.07	1.76
He-Ne laser-plasma	1.66	1.25	0.394
Diode green laser-plasma	1.51	1.13	0.512
Nd:YAG laser-plasma	2.73	2.05	0.782

the presented data in Table 1 and Fig. 5 is obtained. The small uncertainty shown in the electron temperature belongs to the room temperature of about ≈ 0.03 eV. While the uncertainty of ± 0.2 was incorporated, which is according to the nitrogen ion lines broadening (14).

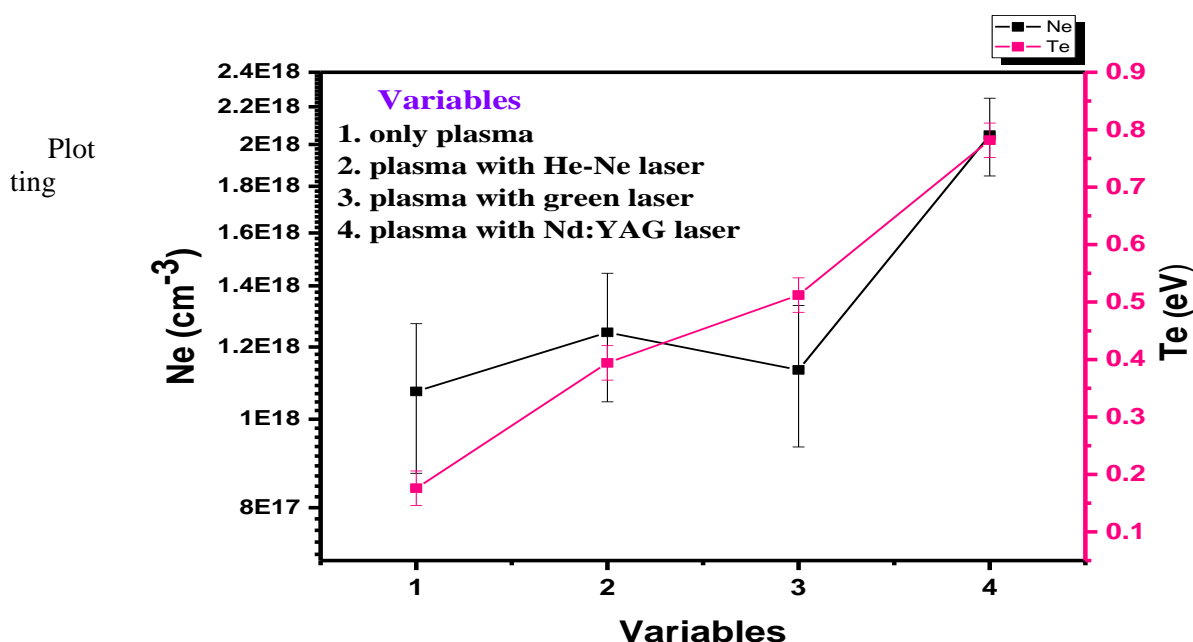


Figure 5. The increasing of the plasma electron density and the electron temperature according to the interaction with laser beams.

Figure 5 shows the behavior of electron density and electron temperature of plasma due to the interaction with the laser beams. It is obvious in this figure that the temperature of the plasma electron rises with increasing the power of laser beam independently from the wavelength of the laser. While the density of electrons in the plasma shows a slight decrease when interacting with the green laser. Returning to Eq. 4, it can be found that the electron density depends on the FWHM of the highest peak in the plasma spectrum. The value of FWHM is about 1.51 with the green laser in between 1.66 and 2.73(Fig.3) with He-Ne laser, Nd:YAG laser, respectively. This interpreter the behavior of the density of plasma electrons shown in Fig. 5.

It can be seen from the experimental data presented above that the characteristics of the

spectral emission intensities of plasma are enhanced through the interaction with laser leading to a change into the peak position of plasma spectra. When plasma emission interacts with the laser, the electrons of plasma accelerate and gain energy from the electric field of the laser (10), which is promising high-intensity plasma production for many applications e.g. plasma for material processing surfaces.

Furthermore, laser-plasma interaction opens an additional investigation of generating new light sources for optical component testing, applications requiring long lamp life e.g. spectroscopy application, advanced imaging/illumination, environmental analysis (15, 16). Plotting the measured data of laser-plasma interaction in one figure explain clearly the changing in the plasma spectrum through these interactions.

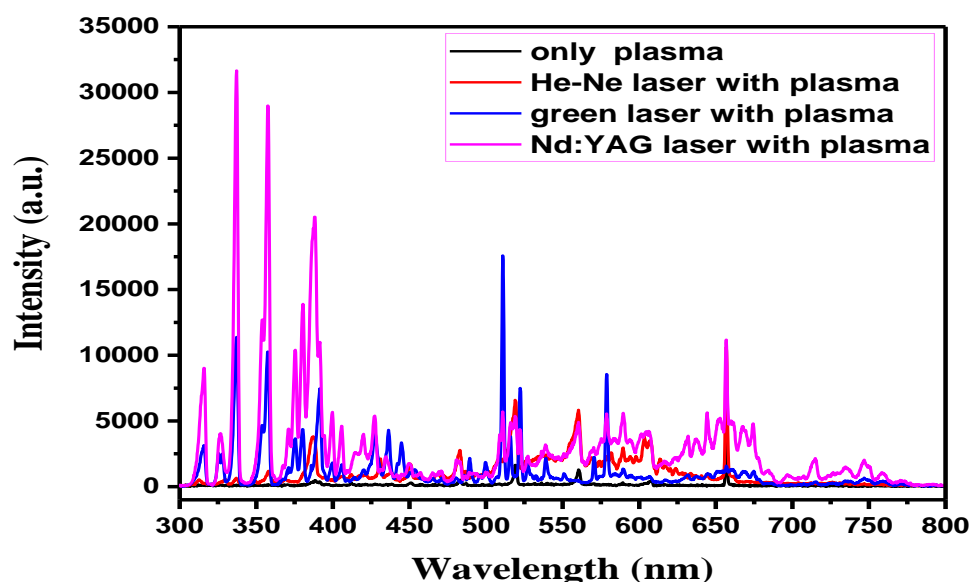


Figure 6. plasma-laser interaction spectra, measured at the same parameters seated from the spectrometer.

Figure 6 shows the plasma spectrum in addition to the laser-plasma interaction spectra. The enhancement of plasma spectra by laser interaction is clear, where there is an overall noticeable increase in the plasma emission spectral range especially in the range of 300 to 700 nm, an additional small increase in the range of 700 to 800 nm was also observed. The photons of laser transfer energy into the plasma electrons through the interaction leading to rising the intensity of plasma in (17, 18).

By subtracting the plasma spectrum from the measured spectra resultant from the interaction of plasma-lasers, new spectra from the peak positions and intensity were obtained. The obtained spectra were plotted as shown in Fig.7. By doing a comparison between the plasma spectrum and obtained spectra (Fig.7), the plasma spectrum shows only one peak in the range of (200 to 450) nm, while a significant multiple peaks are located in this range appearing from the interaction of lasers-plasma. The new wavelengths generation in the mentioned range independently on the laser wavelength is due to the nitrogen gas (14). In the range of (450 to 800) nm, a few peaks are located in the plasma spectrum. It was also observed that the position of the highest peak in the presented spectra moves backward to UV spectral range and the positions depend on the wavelength of the involved laser in the interaction.

Generating new spectral ranges from the interaction of lasers-plasma is a promising new generation of light sources for a wide area of applications. Light sources such as xenon or

mercury arc lamps produce light that is widely used in the range of UV-VIS measurements. These lamps consist of an anode and cathode that is used to excite xenon or mercury gas in the lamp tube. An electrical discharge is generated between the anode and the cathode to provide energy for the excited gas to release light by ionizing gas while the light source is operating. During this process, the anode and the cathode become very hot according to the electrical discharge that is connected to the ionized gas located between the anode and the cathode. As a result, the anode and / or cathode are burned and may emit particles that could contaminate the light source. In addition, these arc lights do not provide enough brightness for some applications, especially in the ultraviolet spectrum. Furthermore, the position of the arc can be unstable in these lamps (19, 20).

Based on our results, a new broadband light source can be generated from the combination of laser and plasma. When the plasma emission shouts with a laser beam, new wavelengths can be generated. It can also be concluded that the properties of the obtained light depend on the ionized gas and used laser. In addition, the generated wavelengths depend on the kind of ionization ability gas used in the measurements. While the laser beam has power stability and the plasma emission has high brightness, the generated light can have both properties. Compared to the well-known light sources and LEDs operated in UV-VIS, these light sources present as an attractive light source for many applications especially in fluorescence spectroscopy (21, 22).

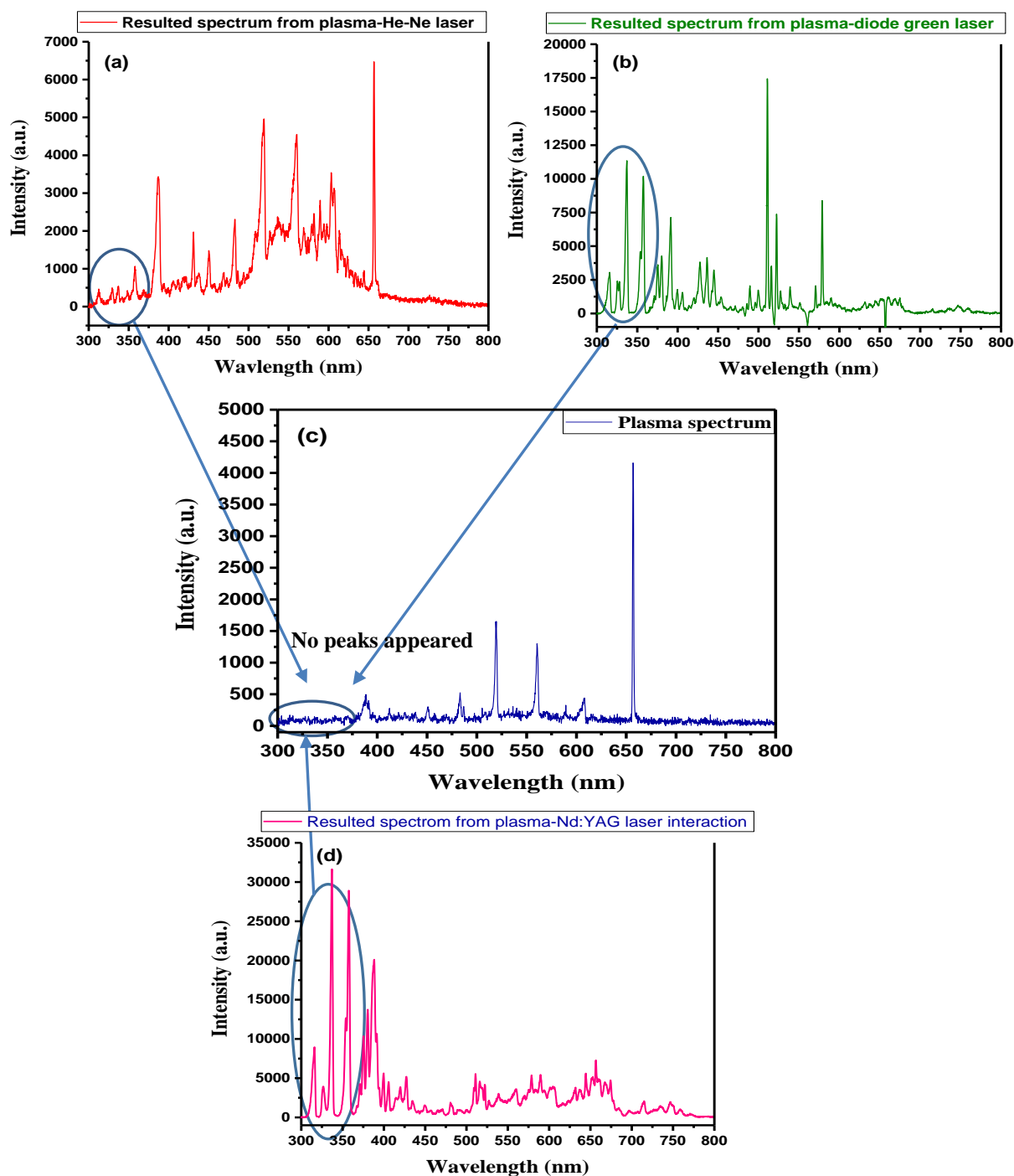


Figure 7. shows the comparison between the spectrum of plasma and the resultant spectra from the interaction of laser-plasma, a) He-Ne laser-plasma, b) diode green laser-plasma, c) only plasma spectrum, d) Nd:YAG laser-plasma.

Conclusion:

Laser-plasma interaction shows efficient enhancement of the plasma spectral range in the measured data obtained in this investigation. New wavelengths spectral range are observed from the interaction of lasers-plasma. The resultant spectra depend on the wavelength and intensity of the involved lasers in these measurements. The intensity of plasma spectral peaks is enhanced from

several thousand to several tens of thousands during the laser-plasma interaction processes. Three types of laser and DC glow discharge plasma under the vacuum chamber are incorporated into the measurements. The electron density is increased from 1.07×10^{18} to $2.05 \times 10^{18} \text{ cm}^{-3}$ as the intensity of laser increases. As a result of the interaction, the electron temperature of the plasma is raised from 0.176 to 0.782 eV.

According to our results, a novel broadband light source can be achieved. This can be offered from the combination of laser light and plasma emission. a light source that generates broadband, high brightness light, intensity stability, long life, low cost and make this source incredibly useful is needed in many applications. For further investigation, selecting other ionization able gases and figuring out the output of the spectral ranges is planned.

Authors' declaration:

- Conflicts of Interest: None.
- We hereby confirm that all the Figures and Tables in the manuscript are mine ours. Besides, the Figures and images, which are not mine ours, have been given the permission for republication attached with the manuscript.
- Ethical Clearance: The project was approved by the local ethical committee in University of Baghdad.

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توليد نطاق طيفي جديد من خلال تفاعل الليزر مع البلازما

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الخلاصة:

تم بحث البلازما عالية الكثافة المنتجة بالليزر على نطاق واسع في الكثير من الدراسات. أما في هذا البحث، فقد لوحظ نطاق طيفي جديد في الأطياف الناتجة من تفاعل الليزر والبلازما، والذي يفتح نقاشات جديدة لتوليد مصدر ضوء جديد. علاوة على ذلك، تم تحسين خصائص البلازما من خلال عملية تفاعل الليزر مع البلازما. لقد تم تضمين ثلاثة أنواع من الليزر في القياسات، ليزر الهليوم-نيون بالنمط المستمر، ليزر دايود الأخضر بالنمط المستمر، وليزر النديميوم-ياك النبضي. أما بالنسبة إلى منظومة البلازما، فقد تم اعتماد منظومة ال (DC) البلازما المفرغة. تم تقييم القمم الطيفية للبلازما الناتجة من المنظومة، والتي تدل على غاز النيتروجين. أوضحت النتائج بأن شدة البلازما قد ازدادت من عدة آلاف إلى عدة عشرات الآلاف من خلال عملية تفاعل ليزر النديميوم-ياك مع البلازما، وأن هذه الزيادة في شدة البلازما مع زيادة شدة الليزر تحدث بغض النظر عن طول موجة الليزر الداخل في هذا التفاعل. تم توسيع ما يسمى (العرض الكامل بمقدار نصف الحد الأقصى FWHM) بالنسبة إلى أعلى قمة في طيف البلازما من 1.43 إلى 2.37. وفقاً لصيغة حساب كثافة البلازما والتي تعتمد على FWHM، زادت كثافة البلازما من (1.07×10^{18}) إلى (2.05×10^{18}) سم⁻³ مع زيادة عرض أعلى قمة في الطيف. أن طاقة الكترون البلازما قد ازدادت كنتيجة للتفاعل من 0.176 إلى 0.782 الكترون فولت. كما لوحظ أن موضع أعلى قمة في طيف البلازما يعتمد على طول موجة الليزر الداخل في التفاعل.

الكلمات المفتاحية: ليزر بالنمط المستمر، بلازما تفريغ التوهج، مصادر الضوء عالية السطوع، تفاعل ليزر-بلازما، الليزر النبضي.