Plasma characteristics of Ag:Al alloy produced by fundamental and second harmonic frequencies of Nd:YAG laser

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Abstract

In this work, the spectra for plasma glow produced by pulse Nd:YAG laser (λ=532 and 1064nm) on Ag:Al alloy with same molar ratio samples in distilled water were analyzed by studying the atomic lines compared with aluminum and silver strong standard lines. The effect of laser energies of the range 300 to 800 mJ on spectral lines, produced by laser ablation, were investigated using optical spectroscopy. The electron temperature was found to be increased from 1.698 to 1.899 eV, while the electron density decreased from 2.247×10^{15} to 5.08×10^{14} cm^{-3} with increasing laser energy from 300 to 800 mJ with wavelength of 1064 nm. The values of electron temperature using second harmonic frequency are greater than of 1064 nm, which increased from 2.405 to 2.444 eV, while the electron density decreased from 2.210×10^{15} to 1.516×10^{15} cm^{-3} with increasing laser energy for the same energy range.

Key words
Pulse laser, spectroscopy, Boltzmann plot, plasma characteristics.

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دراسة خصائص البلازما لسبيكة Ag:Al المتولدة بواسطة ليزر Nd:YAG وللترددات الأساسي و التوافقي

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الخلاصة

تم في هذا البحث، دراسة أطياف توهج البلازما التي تنتجها ليزر نبضي وبطول موجي 532 و 1064 نانومتر داخل الماء المقطر على سبيكة Ag:Al و بنسب مولية متساوية من خلال دراسة الخطوط الذرية للألومنيوم والفضة و مقارنتها مع القيم العيارية. تم دراسة تأثير طاقة الليزر المستخدم للمدى من 300 الى 800 ملي جول على الخطوط الطيفية، التي تنتج مع اقتلاع المادة بالليزر، وذلك باستخدام التحليل الطيفي الضوئي. فقد أظهرت النتائج، أن درجة حرارة الإلكترون تزداد من 1.698 الى 1.899 إلكترون فولت، في حين انخفضت كثافة الإلكترونات من2.247×10^{15} الى 5.08×10^{14} سم^{3} مع زيادة طاقة الليزر من 300 الى 800 ملي جول باستخدام الطول الموجي 1064 نانومتر. بينما بينت النتائج أن قيم درجة حرارة الإلكترون باستخدام التردد التوافقي الثاني أكبر من قيم الطول الموجي لل1064 نانومتر، حيث ازدادت من 2.405 الى 2.444 إلكترون فولت، في حين انخفضت كثافة الإلكترونات من 2.210×10^{15} الى 1.516×10^{15} سم^{3} مع زيادة طاقة الليزر لنفس المدى.

Introduction

Plasma diagnostics are used to obtain information about the nature of plasma, such as the chemical compositions and species of the plasma, density of the plasma, electron temperature [1]. Pulsed laser-induced plasmas of metals and alloys have more interest as they used in several applications such as synthesize of Nano-particles [2] investigation on elemental content [3] spectroscopic studies [4]. Light emitted in a wide range for spectroscopic analysis from the plasma generated by high- power laser pulses were detected and the resulting spectrum distribution. A spectrum often consists of a number of characteristic spectral lines of a particular atom or ion [5].

The electron temperature of plasma was calculated using Boltzmann relation [6]:

$$Ln\left(\frac{I_{mn}\lambda_{mn}}{g_m A_{mn}}\right) = \left(\frac{E_m}{KT_e}\right) + \left(\frac{N(T)}{U(T)}\right) \quad (1)$$

where λ_{mn}, I_{mn}, g_m, and A_{mn} are the wavelength, intensity, statistical weight, and transition probability between the transition states of upper level (m) and lower level (n), respectively.

The electron density was calculated using Saha-Boltzmann equation for atom and ion spectral lines emitted from the plasma [7]:

$$n_e = \frac{2(2\pi m_e kT)^{3/2}}{h^3} \frac{I^I_{mn} A_{jk} g^{II}_j}{I^{II}_{jk} A_{mn} g^I_m} e^{-(E_{ion}+E^{II}_j - E^I_m)/kT} \quad (2)$$

where E_{ion}, E_m and E_j are the ionization energy, the upper level energies of neutral and single ionized transitions, respectively.

The Coulomb interaction range in plasma is reduced due to the screening effect. The screening scale length, called the Debye length (λ_D) was calculated as follows [8]:

$$\lambda_D = \left(\frac{k_\beta T_e}{4\pi e^2 n_{0e}}\right)^{1/2} \approx 743\left(\frac{T_e(eV)}{n_{0e}(cm^{-3})}\right)^{1/2} \quad (3)$$

An important criterion for an ionized gas to be a plasma is that it should be dense enough so that $L \gg \lambda_D$.

While the plasma frequency can be calculated as follows [7]:

$$\omega_p = \sqrt{\frac{N_e q_e^2}{\epsilon_o m_e}} \quad (4)$$

plasma oscillations can only develop if the mean free time τ_n between collisions is long enough compared to the oscillation period. This condition is a criterion for an ionized gas to be considered a plasma.

The concept of Debye shielding developed if the number of particles in a Debye sphere, $N_D \gg 1$. [7]

$$N_D = n_e\left[\frac{4\pi\lambda_D^3}{3}\right] = \frac{1.38\times10^6 T_e^{3/2}}{n_e^{1/2}} \quad (5)$$

where T_e in K.

Experimental part

Ag:Al alloy were prepared using equal molar quantities of silver and aluminum powder and mix them by mechanical motor with steel balls at 10 minutes. A piston under a pressure of 3.5 tons was used to make a disk of 1 gm Ag:Al alloy with 0.9 cm diameter and 0.3 cm thickness. The sample was put in the bottom of 5 ml quartz tube filled by distilled water. The samples were bombarded by Nd:YAG pulse laser (9 ns duration and10 Hz frequency) with two wavelengths (532 and 1064 nm) and several energies (300, 400, 500, 600, 700 and 800 mJ). The emitted spectrum from the surface of samples was studied by optical fiber to be analyzed using a spectrometer connected with a computer to study the effect of laser energy and wavelength on the properties of the produced plasma.

Results and discussion

We have produced plasma from the laser interaction with Ag:Al alloy target using Q-switched Nd:YAG in distilled water.

Ag:Al target plasma in water using 1064 nm laser

The optical emission spectra of Ag:Al plasma in distilled water were recorded by using optical emission spectroscopy technique with 1064 nm Nd-YAG laser. Fig. 1 shows the spectroscopic patterns for laser induced on Ag:Al surface with different laser energies from 300 to 800 mJ, with 100 mJ step in distilled water. A comparison between observed peaks and standard Ag I, Ag II, Al I and Al II data [9] were done. This figure shows that the dominant peaks identify with Ag II standard lines. Most of the peaks appeared within the range of (160 to 280 nm), except for some peaks belonging to Ag I located at (520.50 and 546.23 nm) and for Al I (at 596.01 nm). The emission spectrum intensity increased with increasing laser energy this results is agreement with Huang et al. [10].

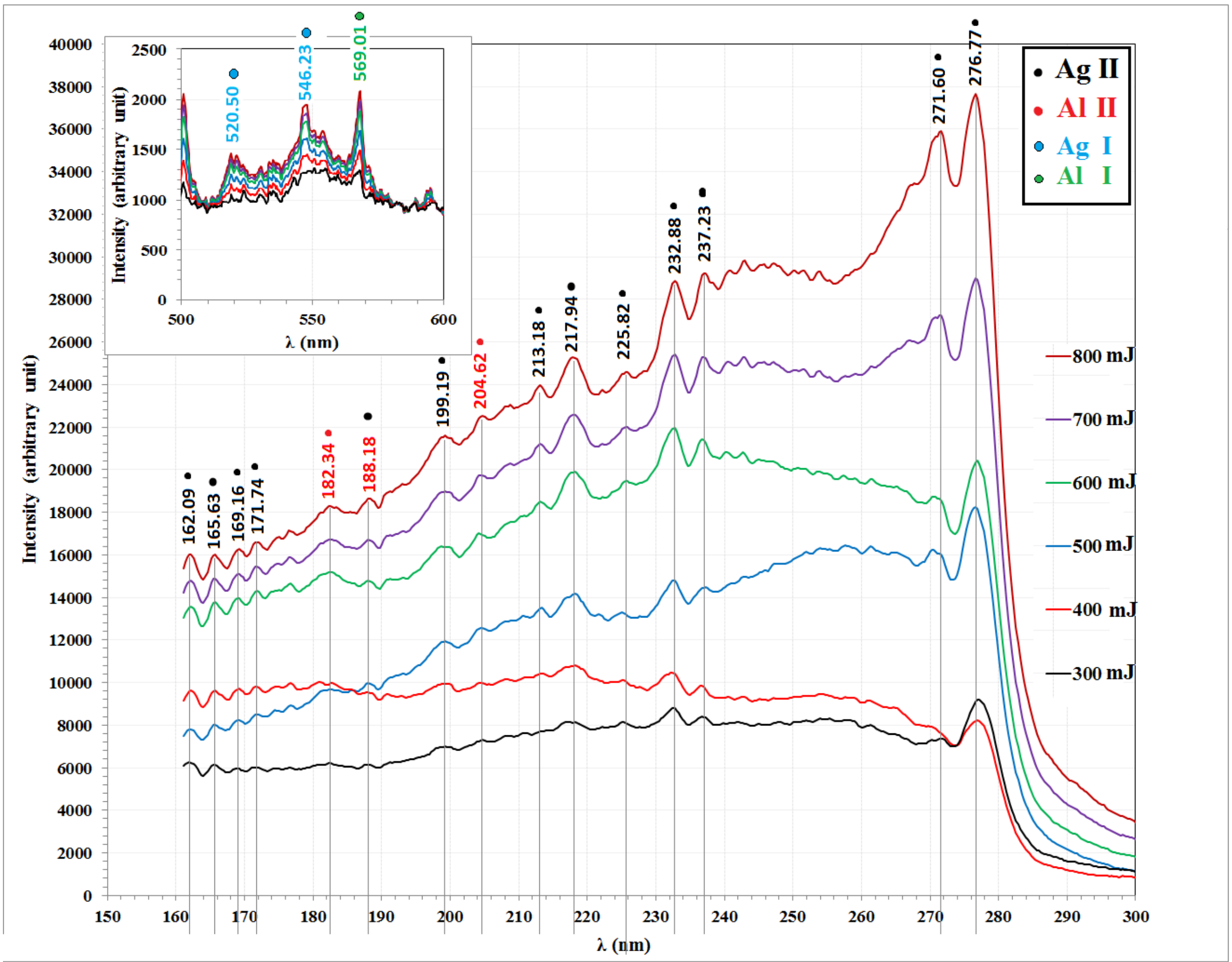

Fig. 1: Emission spectra induced by 1064 nm laser, with different laser energies for Ag:Al alloy in distilled water.

The value of T_e is obtained from the Boltzmann plot method, as shown in Fig. 2, from the analysis of the nine recorded Ag II lines for plasma induced on Ag:Al alloy in distilled water using 1064 nm laser, at different laser energies 300, 400, 500, 600, 700 and 800 mJ. The values of T_e were estimated from the inverse of the slope of a linear best fit for the result values.

The fitting equations and the R^2 were shown in the figure for all fitting lines. R^2 is a statistical coefficient indicating the goodness of the linear fit which takes a value between (0, 1). The better one have R^2 value closer to 1 [11].

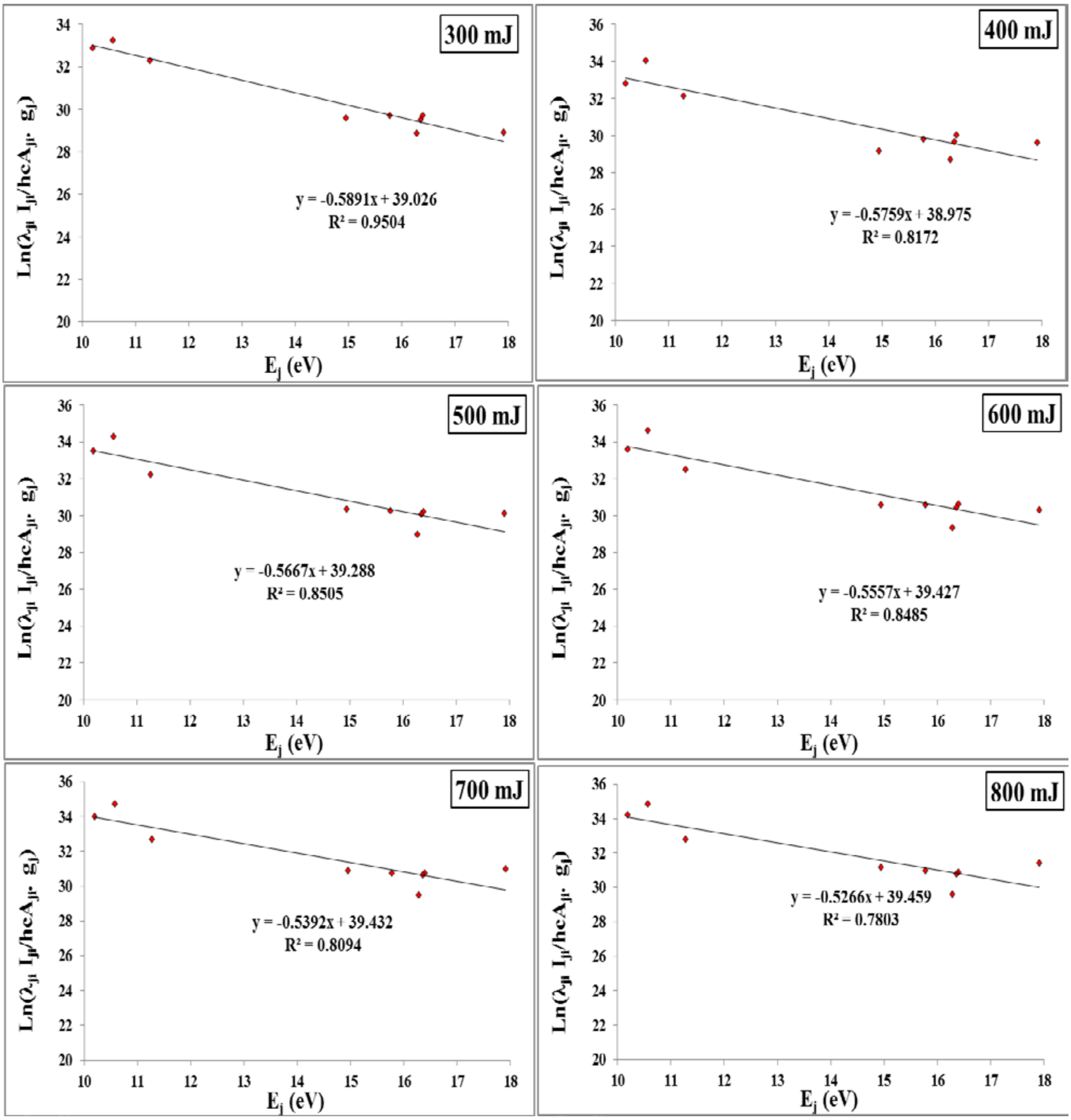

Fig. 2: Boltzmann plot method from the analysis of nine Ag II lines for Ag:Al alloy in distilled water using 1064 nm laser, with different laser energies. The best fit straight line, its equation and average relative standard deviation values R^2 are shown.

Electron temperature (T_e) was calculated from the slope of fitting line using Eq. (5) and electron density (n_e) using Saha–Boltzmann equation. Fig. 3 shows the variation of T_e and n_e with laser energy. This figure shows that the T_e increase with increasing laser energy, while n_e decrease with increasing laser energy when varies from 300 to 800 mJ.

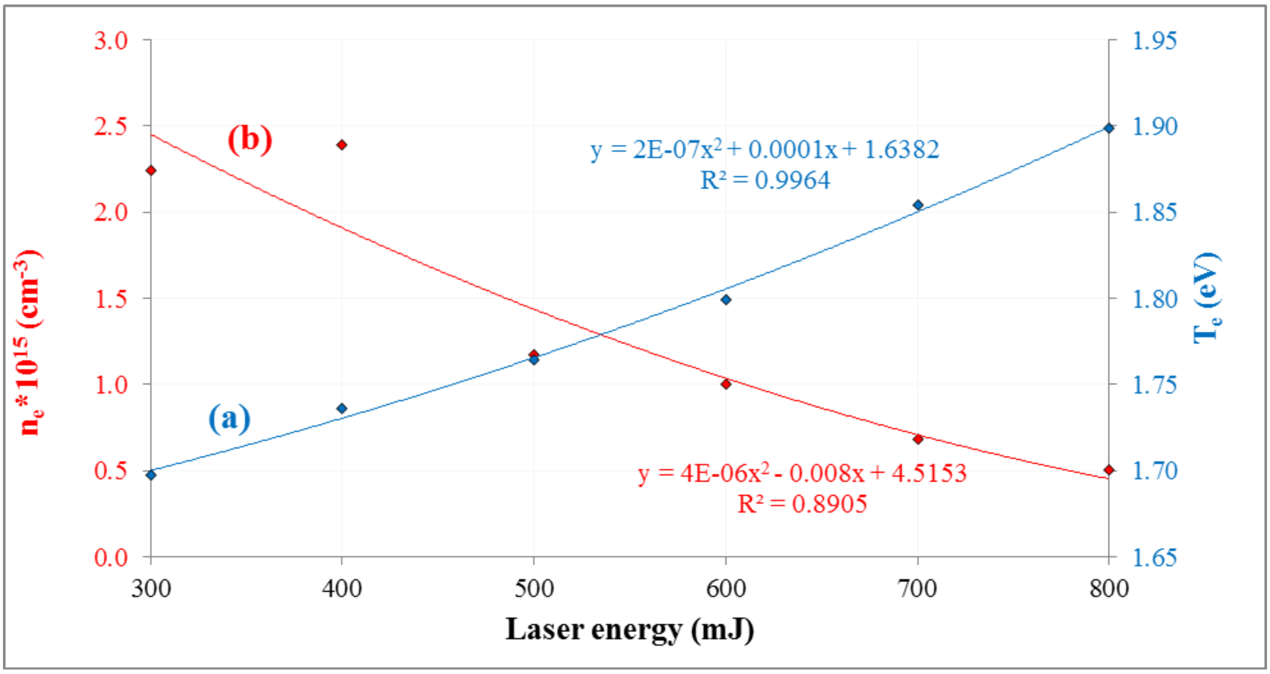

Fig. 3: The variation of (a) T_e and (b) n_e with laser energy for plasma indused on Ag:Al alloy in distilled water using 1064 nm laser.

Table 1 shows the calculated values of Debye length (λ_D), plasma frequency (f_p) and Debye number (N_d) at different laser energies. All calculated plasma parameters were satisfied the plasma conditions.

Table 1: Plasma parameters calculated from spectroscopy lines for Ag:Al alloy in distilled water using 1064 nm laser, with different laser energies.

Laser energy (mJ)	f_p (Hz) *10^{11}	λ_D (cm)	N_d *10^4
300	4.257	0.00020	8.017
400	4.391	0.00020	7.943
500	3.075	0.00029	11.620
600	2.840	0.00031	12.957
700	2.343	0.00039	16.429
800	2.025	0.00045	19.697

Ag:Al target plasma in distilled water using 532 nm Nd:YAG laser

Fig. 4 shows the spectroscopy patterns for laser induced on Ag:Al surface with different laser energies 300, 400, 500, 600, 700 and 800 mJ. Most of the peaks appeared within the range of (160 to 280 nm), except for some peaks belonging to Ag I (at 338.62 nm). This result is agreement with Musadiq et al. [12]. The emission spectrum intensity increase with increasing laser energy. The dominant peaks identify belong Ag II standard lines.

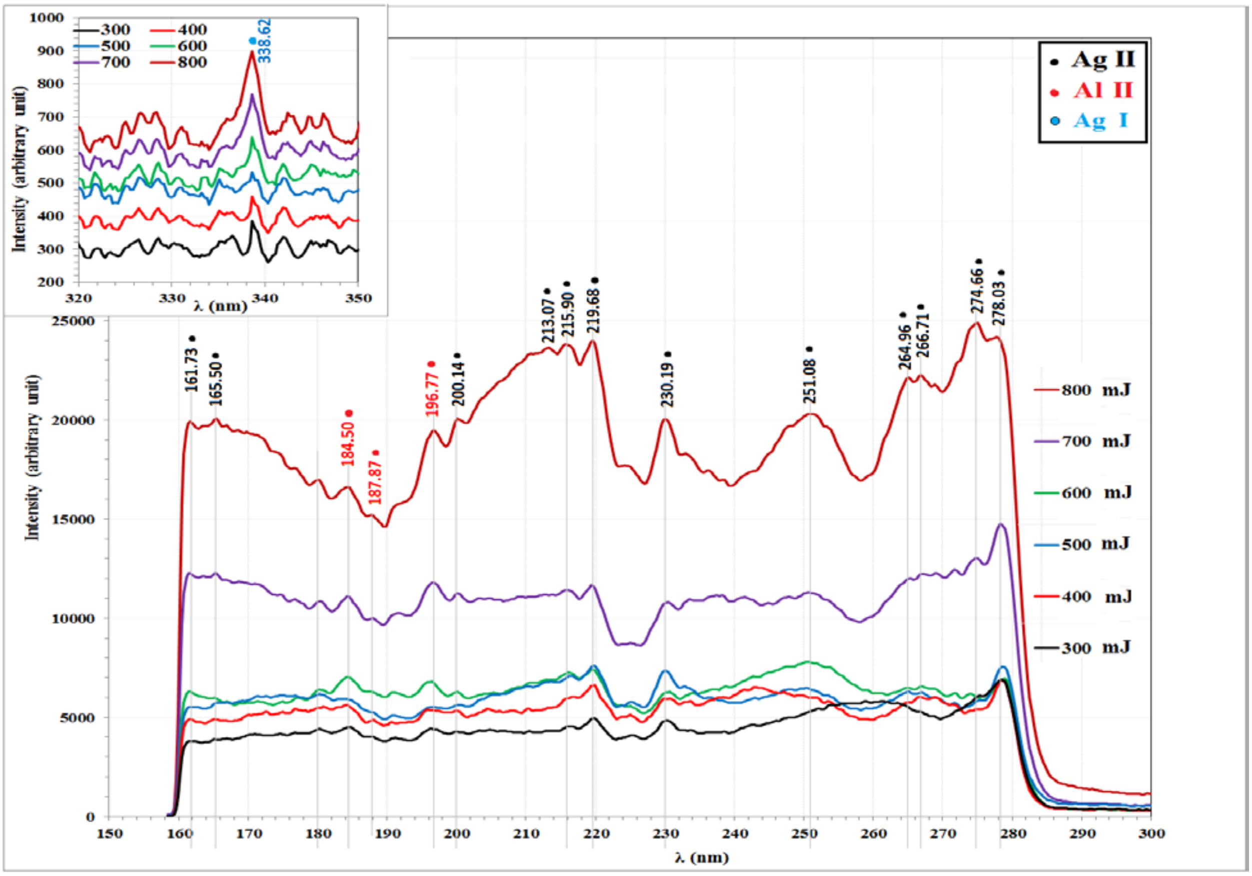

Fig. 4: Emission spectra induced by 532 nm laser, with different laser energies for Ag:Al alloy in distilled water.

The values of T_e were obtained from the Boltzmann plot, as shown in Fig. 5, from the analysis of the nine recorded Ag II peaks for plasma induced on Ag:Al alloy in distilled water using 532 nm laser, with different laser energies 300, 400, 500, 600, 700 and 800 mJ. The values of T_e were estimated from the inverse of the slope of a linear best fit for the result values. The fitting equations and R^2 were shown in the figure for all fitting lines.

The same behavior for plasma temperature (T_e), T_e increase with laser energy, and electron density (n_e) in 532 nm as in 1064 nm and at different laser peak powers in distilled water as shown in Fig. 6, but with higher values in 532 nm because the high kinetic energy gained to ejected electrons from higher photons energies [13]. n_e increase reaching maximum values at 600 mJ laser energy, then decrease with more laser energy.

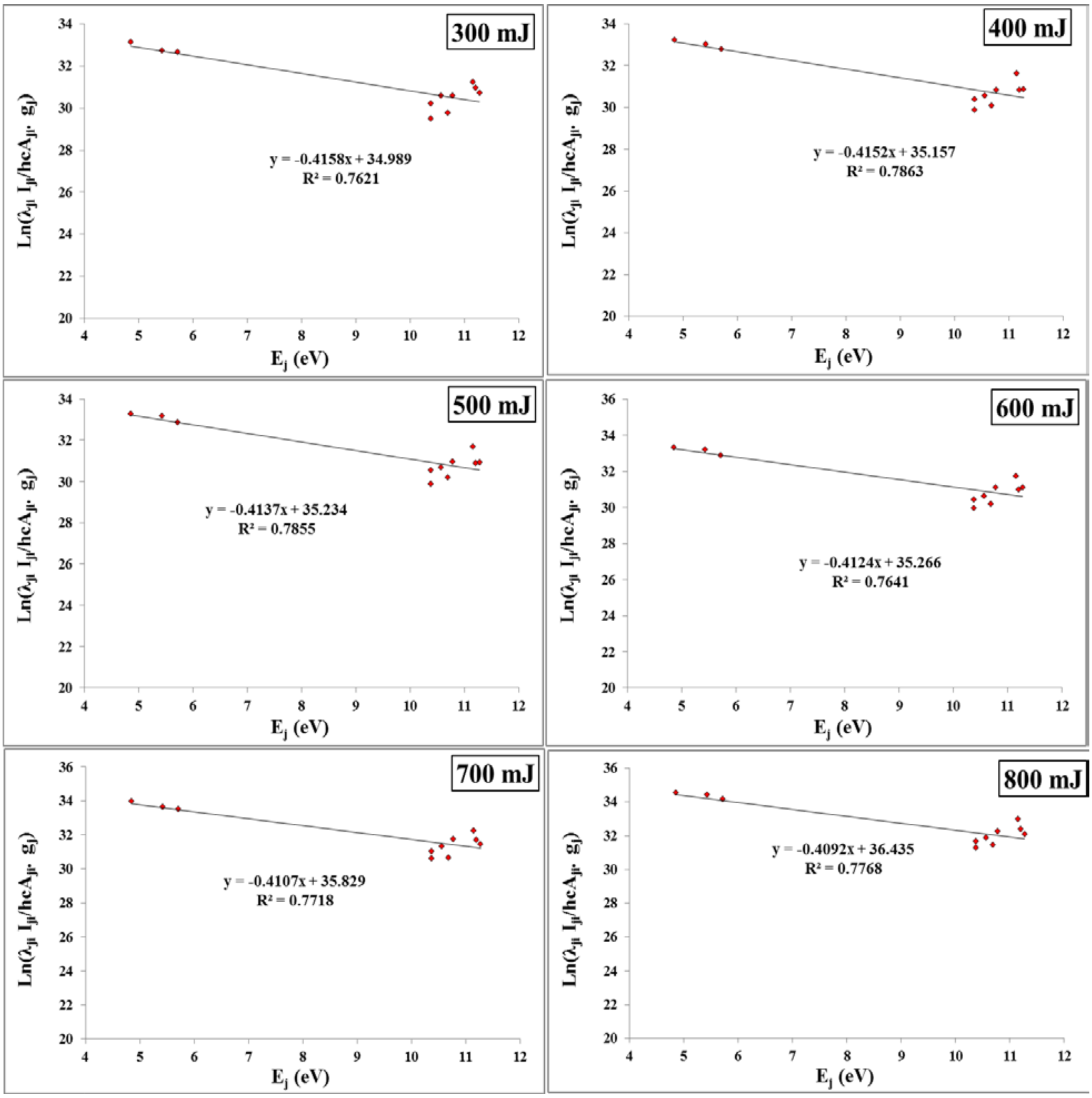

Fig. 5: Boltzmann plot made from the analysis of nine Ag II lines for Ag:Al alloy in distilled water using 532 nm laser, with different laser energies. The best fit straight line, its equation and average relative standard deviation values R^2 are shown.

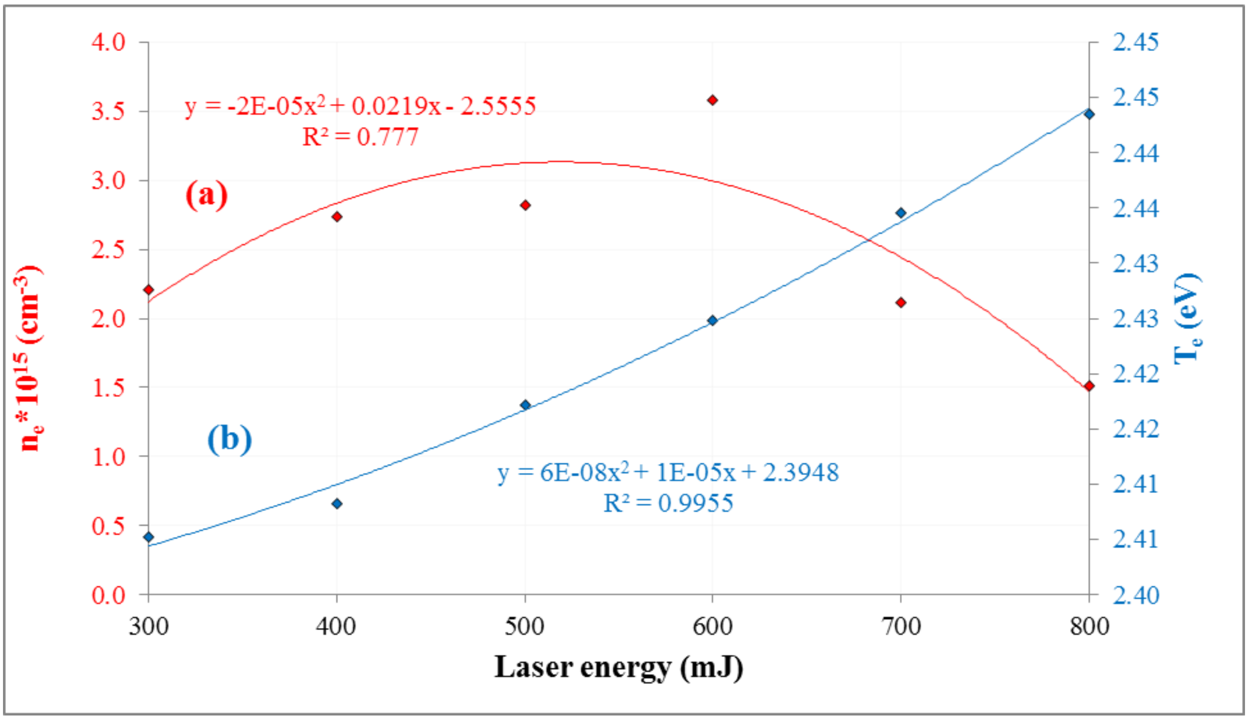

Fig. 6: The variation of (a) T_e and (b) n_e with laser energy for plasma indused on Ag:Al alloy in distilled water using 532 nm laser.

Table 2 shows Debye length (λ_D), plasma frequency (f_p) and Debye number (N_d) at different laser energies.

Table 2: Plasma parameters calculated from spectroscopy lines for Ag:Al alloy in distilled water using 532 nm laser, with different laser energies.

Laser energy (mJ)	f_p (Hz) *10^{11}	λ_D (cm)	N_d *10^4
300	4.222	0.00025	13.633
400	4.699	0.00022	12.122
500	4.767	0.00022	12.015
600	5.374	0.00019	10.710
700	4.132	0.00025	14.014
800	3.497	0.00030	16.650

Fig.7 shows the spectroscopy patterns, at the range 550 to 900 nm, for laser induced on Ag:Al surface using 532 nm laser. A set of peaks appeared and with similar position for all samples within the range of 580 to 890, previous studies have shown that one of the emission band for distilled water molecule within this range [14].

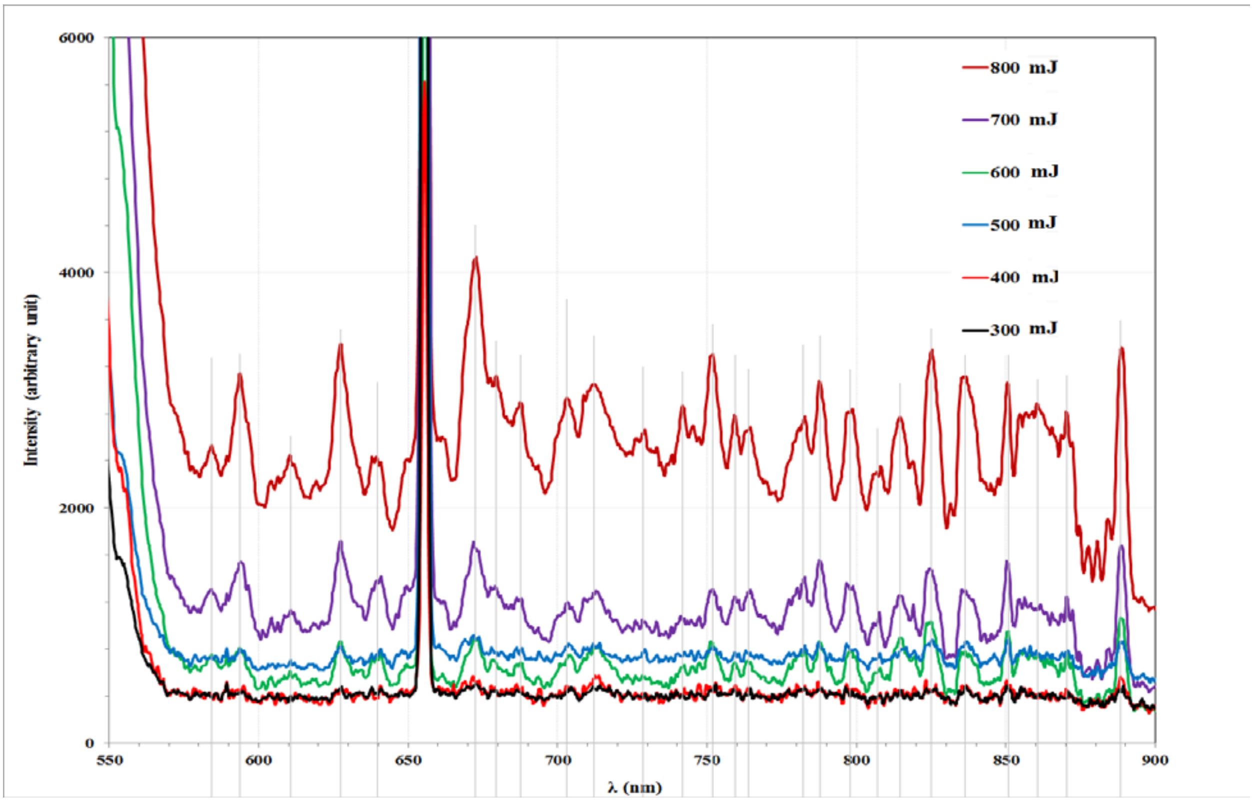

Fig. 7: Emission spectra induced by 532 nm laser, with different laser energies for Ag:Al alloy in distilled water.

Conclusions

Study the effect laser energies on spectra for plasma glow produced by pulse Nd:YAG laser for different wavelength (λ=532 and 1064nm) on Ag:Al alloy show many points as follows:

- Using 1064 nm laser, the electron temperature increase exponentially from 1.698 to 1.899 eV, while the electron density decrease from 2.247×10^{15} to 5.08×10^{14} cm^{-3} with increasing laser energy from 300 to 800 mJ.
- Electron temperature using 532 nm are greater than with 1064 nm, and increase exponentially from 2.405 to 2.444 eV, while the electron density decrease from 2.210×10^{15} to 1.516×10^{15} with increasing laser energy from 300 to 800 mJ.
- All plasma parameters satisfy plasma conditions.
- New peaks appeared in the range of 580 to 890 when we use 532 nm laser corresponding to one of emission band for water molecules.

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