المجلة العلمية لجامعة الملك فيصل
The Scientific Journal of King Faisal University

العلوم الأساسية والتطبيقية
Basic and Applied Sciences

Influence of Laser Energies on Tin Oxide Nanoparticles Plasma Parameters Prepared by Nd:YAG Laser

تأثير طاقات الليزر على معلمات البلازما لأكسيد القصدير النانوي المحضر بواسطة ليزر ND:YAG

Madyan A. Khalaf[1] **and Wasnaa J. Hmood**[2]
[1] Department of Physics, College of Science, Mustansiriyah University, Baghdad, Iraq
[2] Department of Graduate Studies, Mustansiriyah University, Baghdad, Iraq

مدين احمد خلف [1] وسناء جليل حمود [2]
[1] قسم الفيزياء، كلية العلوم، الجامعة المستنصرية، بغداد، العراق
[2] قسم الدراسات العليا، الجامعة المستنصرية، بغداد، العراق

KEYWORDS
الكلمات المفتاحية
Tin oxide plasma, Saha-Boltzmann plot, optical emission spectroscopic (OES)
بلازما اكسيد القصدير، طريقة ساها- بولتزمان، طيف الانبعاث البصري

RECEIVED الاستقبال	ACCEPTED القبول	PUBLISHED النشر
23/08/2020	17/10/2020	01/12/2020

https://doi.org/10.37575/b/sci/0009

ABSTRACT

In this study, plasma was generated from laser-induced plasma and the parameters of the plasma were analysed using the optical emission spectroscopy technique. A 1064 nm wavelength Nd:YAG laser with a frequency of 6 Hz within a 9 ns timeframe, was used. The ratio between two spectral lines was used to calculate the temperature of the electron (T_e), while the Saha-Boltzmann method was used to find the density of electrons (n_e) for wavelengths between 170 - 670 nm, by changing the laser energies within the 400 – 900 mJ region. The remaining plasma parameters were also calculated. These included the Debye length (λ_D), the plasma frequency (ω_p) and the number of atoms within the Debye sphere (N_D). Three relationship diagrams illustrate the relationship between laser energy change and the plasma parameter collection. The highest possible electron temperature is 1.453 eV, while the lowest possible temperature is 1.216 eV. The upper limit of the electron density has reached 6.5×10^{18} cm^{-3}, and its lowest value is 1.7×10^{18} cm^{-3}.

الملخص

في هذه الدراسة ، تم تحليل معلمات البلازما بواسطة تقنية طيف الانبعاث البصري بينما تم توليد البلازما بواسطة البلازما المستحثة بالليزر. تم استخدام ليزر الطول الموجي Nd: YAG بطول 1064 نانومتر بتردد 6 هرتز خلال فترة زمنية 9 نانو ثانية. النسبة بين خطين طيفيين هي الطريقة التي تم استخدامها لحساب درجة حرارة الإلكترون (T_e) بينما تم استخدام طريقة Saha-Boltzmann لإيجاد كثافة الإلكترونات (n_e) ضمن الطول الموجي 170-670 نانومتر وتغيير طاقة الليزر داخل المنطقة 400-900 مللي جول. تم حساب بقية معلمات البلازما ، مثل طول ديباي (λ_D) ، وتردد البلازما (ω_p) ، وعدد الذرات داخل كرة ديباي (N_D). توضح ثلاثة مخططات للعلاقة بين تغير طاقة الليزر وجمع معلمات البلازما. القيمة القصوى لدرجة حرارة الإلكترون هي 1.453 eV ، بينما القيمة الأدنى هي 1.216 eV. بلغ الحد الأعلى لكثافة الإلكترون 6.5 × 1018 سم3- ، وأدنى قيمته 1.7 × 1018 سم3-.

1. Introduction

Plasma that is produced by a pulsed laser has a brief temporal lifespan and is temporary in nature due to the rapid evolution of its signature parameters. These parameters are heavily dependent on irradiation environments, such as incident laser strength, scale of the irradiation area and the composition of the atmospheric gas and strain. These parameters also differ significantly in terms of the axial or radial distance from the goal surface under the same radiation circumstances (Harilal et al., 1997). Laser-induced breakdown spectroscopy (LIBS) is a type of atomic emission spectroscopy that utilises plasma as vaporisation, atomisation, excitation medium created by the use of a pulsed laser and directed optical radiation. Elemental-specific lines that are produced from plasma using deteriorating processes are observed by a spectrometer and examined in order to determine the qualitative and quantitative measurements of materials, by measuring their location and length. LIBS attracts considerable interest in various areas for its key attributes: no complicated sample prepare- tion required; relatively simple components in a LIBS instrument; remote detection; in situ real-time analysis; simultaneous multi-element detection. (Li et al., 2018). The potential implementation of LIBS necessitates a deeper comprehension of the essential processes that take place when plasma is observed at various time intervals, taking the specific experimental conditions into consideration. Much of the current scientific material on LIBS aims to detect and examine the different atomic and molecular species found in laser-induced plasma (LIP) (Woods and Parigger, 2014). Plasma and the properties thereof (electron density, electron temperature spatial and temporal behaviour) depend on the thermophysical properties of the object and the parameters of the laser rays. These properties include the pulsed laser, period time and form and laser energy and wavelength (Aadim, 2017).

2. Calculation of Electron Temperature

Any form of interior energy (rotational, vibrational and electronic) represent a single temperature in LTE plasmas, the temperatures of tow line ratio and LET depend on atomic lines intensities (Mazhir, 2018). In this research, the ratio method is one of the most commonly used techniques to determine the optical emission spectrum. It is used to calculate the electron temperature, while the Boltzmann plot method is one of the preferred methods for calculating the electron density (Melnikov et al., 2018).

In the experiment, the ratio method is used to calculate the electron temperature. (The method is commonly used to calculate the electron temperature at which the intensity of two atomic or ion spectral lines at the same ionisation stage can be calculated) . In the local thermodynamic equilibrium (LTE), the plasma temperature is calculated using the following equation (Chen, 2016):

$$T = \frac{-(E_1 - E_2)}{k \ln\left(\frac{I_1 \lambda_1 A_2 g_2}{I_2 \lambda_2 A_1 g_1}\right)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

where I_1 and I_2 are the intensity, g is the statistical weight, A is the transition probability, λ is the wavelength, E_1 and E_2 are the energies of excited state in eV and k is the Boltzmann constant. Electron density describes the number of free electrons per unit volume.

3. Calculation of Electron Density

A precise calculation of the plasma electron temperature is important for the quantitative study of the plasma composition. While many spectroscopic techniques are required for the calculation of the excitation temperatures in LIBS, the Saha-Boltzmann plot method is the most popular (Safi et al., 2019). There is an underlying implicit constraint in the Saha-Boltzmann plot approach. Additionally, it makes use of the community of excited states and typically depends on the presumption that only the

Corresponding Author: Madyan A. Khalaf madyan.a@uomustansiriyah.edu.iq ,009647906813456 المؤلف المراسل: مدين احمد خلف

plasma has been in the LTE (Cristoforetti and Tognoni, 2013). The Saha-Boltzmann equation utilises spectral lines of the same element and successive stages of ionisation. The equation is as follows (Halid et al., 2016):

$$n_e = \frac{I_1}{I_2^*} 6.04 \times 10^{21} (T)^{3/2} e^{\frac{(E_1 - E_2 - X_Z)}{kT}} \quad \text{.....................................} (2)$$

where:

$$I_2^* = \frac{I_2 \lambda_2}{g_2 A_2} \quad \text{.....................................} (3)$$

x_z is the ionisation energy in eV; g_2 is the statistical weight of transition from Level 2 to Level 1; λ_2 is the corresponding wavelength of transition from Level 2 to Level 1; and A_2 is a transition probability from transition from Level 2 to Level 1.

4. Calculation of λ_D, ω_P and ND

After measuring the Debye length, the electron temperature and intensity of the electron can be measured using the following equation (Abbas and Muslim, 2017):

$$\lambda D = \sqrt{\frac{\varepsilon_o \, k \, T_e}{n_e \, q^{2e}}} = 7430 \times \left(\frac{T_e}{n_e}\right)^{\frac{1}{2}} \quad \text{...} (4)$$

The Debye length (λ_D) is directly proportional to the square root of the electron temperature and inversely proportional to the electron density. The plasma frequency is calculated using the equation below (Essa and Aadim, 2019):

$$w_p = \frac{(n_e \, e^2)}{m_e \varepsilon_o} \quad \text{. ....} (5)$$

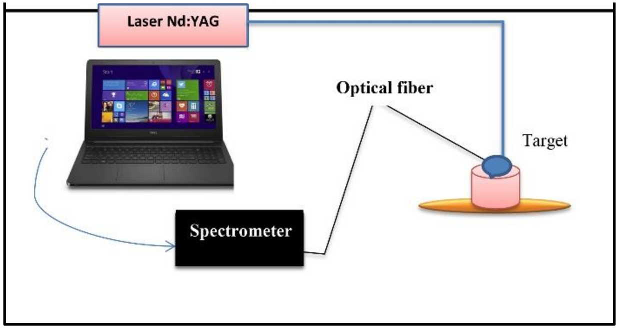
The number of particles in the Debye sphere (N_D) is dependent on the electron density and electron temperature. It represents the second condition for the existence of plasma (N_D>>>1) as follows (Bittencourt, 2004):

$$ND = \frac{4}{3} \pi \, \lambda D3 \, ne \quad \text{.....................................} (6)$$

5. Experiment Set-Up

Nanoparticle oxide powder with a 99.99% level of purity was pressed with a hydraulic piston to form a circular pellet that was 1 cm in diameter and roughly 0.2 cm thick. Figure 1 is a schematic diagram of the experimental installation of the laser-induced plasma spectroscopy (LIPS) device that has been used in this research.

Figure 1: LIPS set-up using an Nd:YAG laser with λ =1064 nm



The LIPS consists of a pulsed Nd:YAG laser with a wavelength of 1604 nm and repetition frequency of 6 Hz. When focused on a target, the laser beam strikes at an angle of 90°. The laser beam evaporates and ionises the target material, creating a plasma plume above the target surface. The optical emission spectroscopy (OES) technique is used to determine the electron temperatures and densities in addition to the plasma frequency. The Debye length and Debye number were determined mathematically.

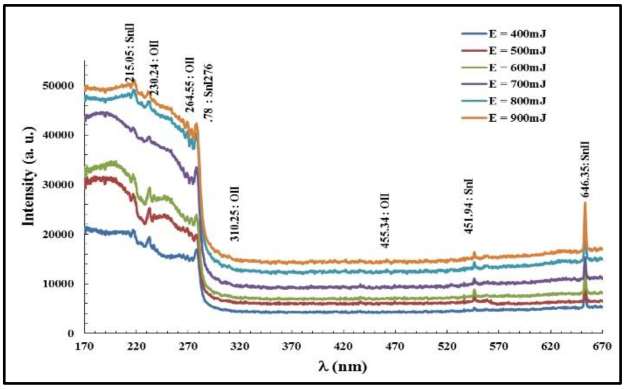
The Surwit S3000-UV-NIR spectrometer is extremely sensitive. It absorbs light energy from the optical fibre and extends it across a fixed grating around the detector. The spectrometer is used with a short response time in every shot. Thus, Surwit (S3000-UV-NIR) spectrometer was used in the setup to determine emission wavelengths and has high goals, relying upon grinding utilised in it, and reacts to a wavelength between 200 – 900 nm. The spectrum of plasma with a different value of energies, prepare by interaction SnO_2 with the laser pulse energy was varied from 400 to 900 mJ.

Each spectrum was obtained over a wavelength range of 170 – 670 nm. The results were discussed and then compared with data from the National Institute of Standards and Technology (NISTdatabase). The plasma parameters were then evaluated (National Institute of Standards and Technology (NIST) Atomic Spectra Database, 2019).

6. Results and Discussion

Optical emission spectroscopy generated by Nd:YAG laser with λ=1064 nm induced tin oxide plasma composition in atmospheric during the range of wavelength 160 nm to 670 nm with different laser energies start from 400 mJ to 900 mJ, as shown in the Figure 2. The emission range comprising all the spectral area that is stable (Sn I), (OI), and ionised (Sn II), (O II). Our knowledge of the plasma temperature and density of the different varieties of plasma is essential for understanding the mechanisms of atomic excitation and ionisation within the plasma.

Figure 2: Demonstrates the emission spectral line of SnO_2 plasma as a function of wavelength with different laser energies



In the figure above, it is clear that the spectral intensity increases as the energy of the laser increases. This is due to an increase in the number of excited and ionised atoms. The electron temperature was calculated using the the line-ratio method, shown in Equation 1, between the two spectral lines for SnO_2. The spectral line of the excited and solid tin oxide was used at the wavelength 451.94: SnI and 646.35: SnII. The density of electrons was calculated using the Saha-Boltzmann method, as per Equation 2.

Table 1 shows the electron temperature (T_e), electron density (n_e), Debye length (λ_D), plasma frequency (ω_p) and Debye number (N_D) SnO_2 targets at different laser pulse energies. The plasma criteria were achieved through the results of the plasma parameters (λ_D, ω_p, and N_D). it was determined [in the experiment] that ω_p increases with laser energy because it is proportional to n_e, while λ_D, and N_D decrease with it.

Table 1: Plasma parameters for SnO_2 at different laser energies

Laser Energy (mJ)	Te (eV)	ne*10 18 (cm^-3)	ωp*10 13 (Hz)	λD *10 -5 (cm)	ND * 10 6
900	1.453	6.5	2.297	3.252	0.943
800	1.366	3.4	1.653	4.381	1.193
700	1.317	2.8	1.497	4.752	1.249
600	1.281	2.4	1.382	5.074	1.296
500	1.275	2.3	1.364	5.130	1.305
400	1.216	1.7	1.186	5.760	1.396

The temperature of the electron (T_e) and the density of the electron (n_e) depend strongly on the laser energy peaks. It can be depicted for both the expected values in Figure 3.

It was noted that the electron temperature (T_e) increases as the laser peak energy increases and that their values are in the range of 1.453 to 1.216 eV. The density of electrons also increases as the laser energy increases, and their values are in the range of 6.5* 10^{18} to 1.7*10^{18} cm^{-3}.

Figure 3: Variation in the temperature and density of the tin oxide compound is a function of different laser energies

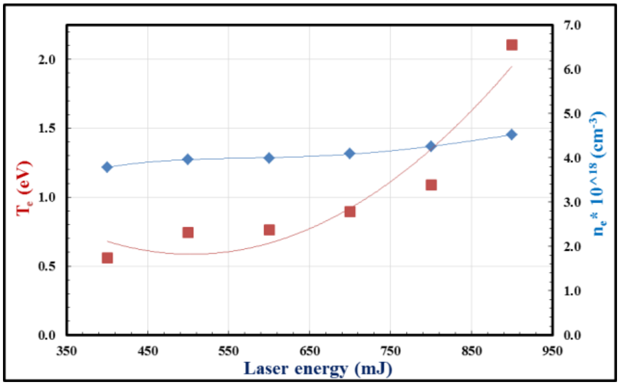


Figure 4 shows a change in the frequency of the plasma as well as the Debye length with respect to the different laser energies, extending from 400 to 900 mJ. It is noteworthy that the plasma response increases with an increase in energy. This is normal because the frequency is directly proportional to the electronic density according to Equation 5. However, the Debye length decreases with an increase in energy and is inversely proportional to the electronic density according to Equation 4. This is similar to the number of atoms in the Debye sphere, which decrease with an increase in energy, as can be seen in Figure 5.

Figure 4: The plasma frequency (ω_p) and Debye length (λ_D) change as a function of laser energy for SnO_2

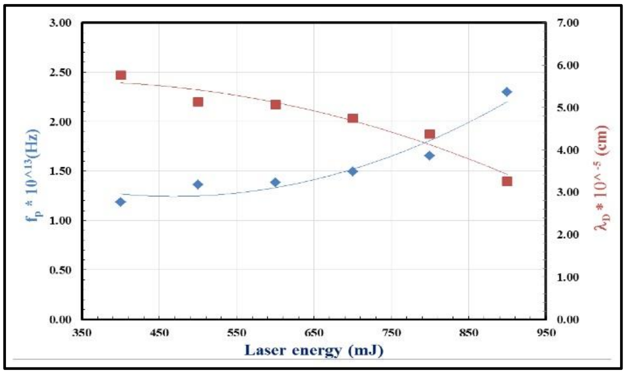
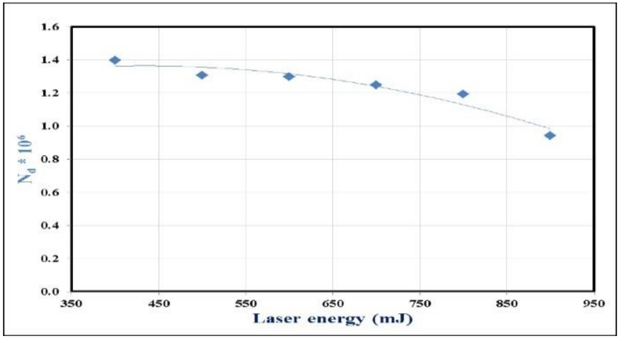


Figure 5: The number of atoms in the Debye sphere (N_D) change as a function of laser energy for SnO2



From the above, it can be noted that the electron density and electron temperature increase as the laser energy increases. These increases were justified for the powerful and substantial effect of the laser peak energy on the intensities of the emission lines, where the intensities of the spectral lines increase with increasing the laser peak energy because of the mass ablation rate of the target also increases.The increase in laser energy will also increase its absorption in the plasma, resulting in more ablation; this leads to an increase in the number of excited atoms and therefore the peaks the spectral line intensities of plasma emissions (Hassan and Aswad, 2019).

7. Conclusion

The plasma was generated by the interaction of the Nd:YAG laser (with a wavelength of 1064 nm, a frequency of 6 Hz and a timeframe of 9 ns) with a nano tin oxide plasma in different energies 500 – 800 mJ. The optical emission spectroscopic technique was performed to measure plasma parameters, such as electron temperature, electron density, plasma frequency, Debye length and Debye sphere. The intensities of various laser peak powers increased with rising laser peak energies. Changes in the above-mentioned parameters with laser irradiance have shown that T_e and n_e rise with an increase in laser energy. All plasma conditions are then achieved.

Bios

Madyan A. Khalaf

Department of Physics, College of Science, Mustansiriyah University, Baghdad, Iraq, 009647906813456, madyan.a@uomustansiriyah.edu.iq

Khalaf is a teacher at Mustansiriyah University, obtained a master's degree from the College of Science, Mustansiriyah University, with a degree of distinction. He specializes in plasma physics. She obtained a bachelor's degree, also with honors, and has many papers published in Scopus-indexed journals. He has published a research paper in one of the reputable Iraqi scientific journals.

Wasnaa J. Hmood

Department of Graduate Studies, Mustansiriyah UniversityPresidency, Baghdad, Iraq, 009647901651426, wasnaa.j.hmood@gmail.com

Hmood obtained a bachelor's degree in mathematics from the College of Science, Mustansiriyah University. She has participated in many scholarly committees. She has interests in the field of data analysis.

References

Aadim, K. A. (2017). Detection of laser-produced tin plasma emission lines in atmospheric environment by optical emission spectroscopy technique. *Photonic Sensors*, **7**(4), 289–93.

Abbas, A. K. and Saif, I. M. (2017). Measurement the parameters of cadmium oxide plasma induced by laser. *International Journal of Recent Research and Applied Studies*, **4**(10), 66–72.

Bittencourt, J. A. (2004). *Fundamentals of Plasma Physics*. (3rd ed.). São José dos Carnpos, São Paulo Brazil: Springer.

Chen, F. F. (2016). *Introduction to Plasma Physics and Controlled Fusion*. (3rd ed.). University of California, Los Angeles, CA: Springer.

Cristoforetti, G. and Tognoni, E. (2013). Calculation of elemental columnar density from self-absorbed lines in laser-induced breakdown spectroscopy: A resource for quantitative analysis. S*pectrochimica Acta Part B: Atomic Spectroscopy*, **79-80**, 63–71. http://dx.doi.org/10.1016/j.sab.2012.11.010.

Essa, M. A. and Aadim, K. A. (2019). Spectroscopic studying of plasma parameters for SnO2 doped ZnO prepared by pulse YAG Laser. *Deposition*, **17**(42), 125–135.

Halid, N. S. T., Zainal, R. and Daud, Y. M. (2016). Estimation of temperature and electron density in stainless steel plasma using laser induced breakdown spectroscopy. *Jurnal Teknologi*, **78**(3), 99–103.

Harilal, S. S., Bindhu, C. V., Issac, R. C., Nampoori, V. P. N. and Vallabhan, C. P. G. (1997). Electron density and temperature measurements in a laser produced carbon plasma. *Journal of Applied Physics*, **82**(5), 2140–2146.

Hassan, R. K., & Aswad M. A. (2019). Study the plasma parameters due to the different energies for laser produced lead oxide plasma. *Indian Journal of Natural Sciences*, **10**(57), 17908–14.

Li, Y., Tian, D., Ding, Y. Yang, G., Liu, K., Wang, C. and Han, X. (2018). A review of laser-induced breakdown spectroscopy signal enhancement. *Applied Spectroscopy Reviews*, **53**(1), 1–35. https://doi.org/10.1080/05704928.2017.1352509.

Mazhir, S. N. (2018). Spectroscopic study of (TiO2)1-x(CuO)x plasma generated by Nd: YAG Laser. *ARPN Journal of Engineering and Applied Science*, **13**(3), 864–69.

Melnikov, A. D., Usmanov, R., Vorona, N., Gavrikov, A. V., Liziakin, G. D., Smironov, V. P. and Timirkhanov, R. A. (2018). Determination of the electron temperature by the line-ratio method in SNF plasma separator. *Physics of Atomic Nuclei*, **81**(11), 1536–40.

National Institute of Standards and Technology (NIST) Atomic Spectra Database. (2019). Retrieved from: https://dx.doi.org/10.18434/T4W30F (Accessed: 10 August 2020).

Safi, A., Tavassoli, H., Cristoforetti, G., Legnaioli, S., Palleschi, V., Rezaei, F. and Togononi, E. (2019). Determination of excitation temperature in laser-induced plasmas using columnar density Saha-Boltzmann plot. *Journal of Advanced Research*, **18**, 1–7.

Woods, A. C. and Parigger, C. G. (2014). Diatomic molecular emission spectroscopy of laser-induced titanium plasma. *Journal of Physics: Conference Series*, **548**(1), 012037.