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RESEARCH PAPER

Energy-Driven Variations in the Spectroscopic Behavior of Silver Plasma Excited at 532 nm

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ABSTRACT

In this paper, the plasma spectrum parameters of silver at 532 nm a wavelength and variable laser energies (100, 150, 200, and 250) mJ were studied using an emission spectrometer. The spectrometer captures the spectrum produced by the silver plasma at different laser energies. The study was conducted under vacuum conditions in air to analyze the resulting plasma spectrum. The electron temperature was calculated for the different laser energies, yielding values of 1.053, 1.221, 1.563, and 1.952 eV, respectively. Additionally, the electron density was determined for all the applied laser energies, it was found that the electron density increases with the rise in laser energies, respectively.

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INTRODUCTION

(LIBS) is a powerful and versatile technique for conducting qualitative and quantitative elemental analyses across a wide range of applications, spanning from materials science to the medical field [1]. This technique involves directing a laser beam onto a target material (solid, liquid, or gas), which leads to its vaporization and the formation of a plasma column, from which an electrical spark is subsequently emitted [2]. Since its introduction, Laser-Induced Breakdown Spectroscopy (LIBS) has proven to be a powerful technique for fast, multi-elemental analysis that is to say spatially resolved surface analysis [3]. LIBS works on a fairly straightforward principle: a sufficiently strong beam laser, primarily concentrated in or confined to the analyzed sample, interacts with the material to cause a dielectric breakdown. This results in the formation of plasma, which is made up of molecules and non-excited and excited atoms, fragments of molecular species, ions and electrons, emits distinctive radiation that, in theory, can be used to determine the material's fingerprint of elemental composition through spectroscopic analysis [4, 5] The extensive applicability and versatility of LIBS make it attractive, especially in the fields of analysis, atomic physics, and plasma. The identification of laser-induced plasmas based on key attributes including temperature. Gaining an advantage over these complex spectroscopic sources and their uses is significantly influenced by the number density and electron density of the different plasma species. One of the most important variables, temperature, is typically measured using spectroscopic techniques [6]. The choice of the appropriate wavelength in LIBS depends on the nature of the sample, the goal of the analysis (surface or depth), and the required

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spectral resolution. Typically, an Nd:YAG laser (1064 nm) is the most commonly used, but when higher resolution and reduced background noise are needed, shorter wavelengths are preferred [7]. However, due to the high reflectivity of silver, it is essential to precisely control the laser incidence angle and pulse energy to minimize energy loss. For effective silver analysis using LIBS, it is preferable to use shorter wavelengths (532 nm or shorter) to achieve a strong plasma and a clear spectrum, especially since the prominent silver lines are located in the ultraviolet range. Longer wavelengths can work but may suffer from weak absorption due to the nature of silver.

The ablated material's emission species can be identified and quantified with the use of the plasma emissions spectrum. Plasma properties are influenced by laser power, wavelength, and pulse life as well as target material chemical and physical characteristics and the surrounding

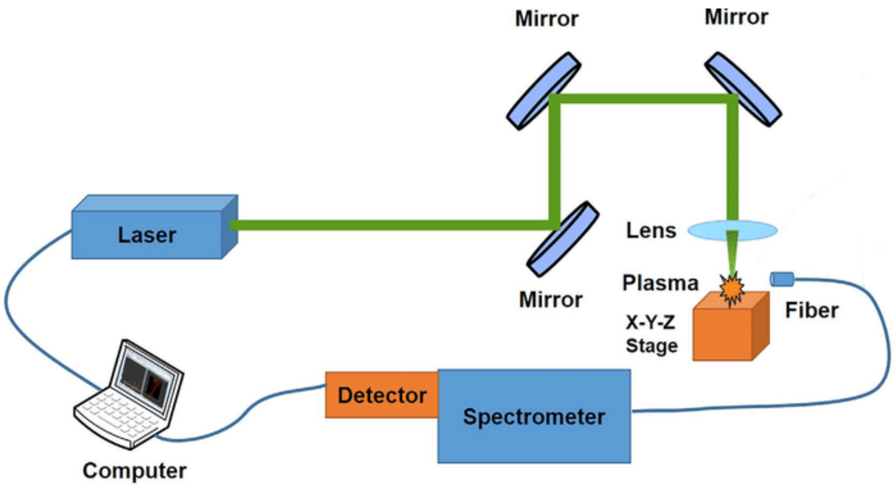

Fig. 1. Schematic diagram of LIBS.

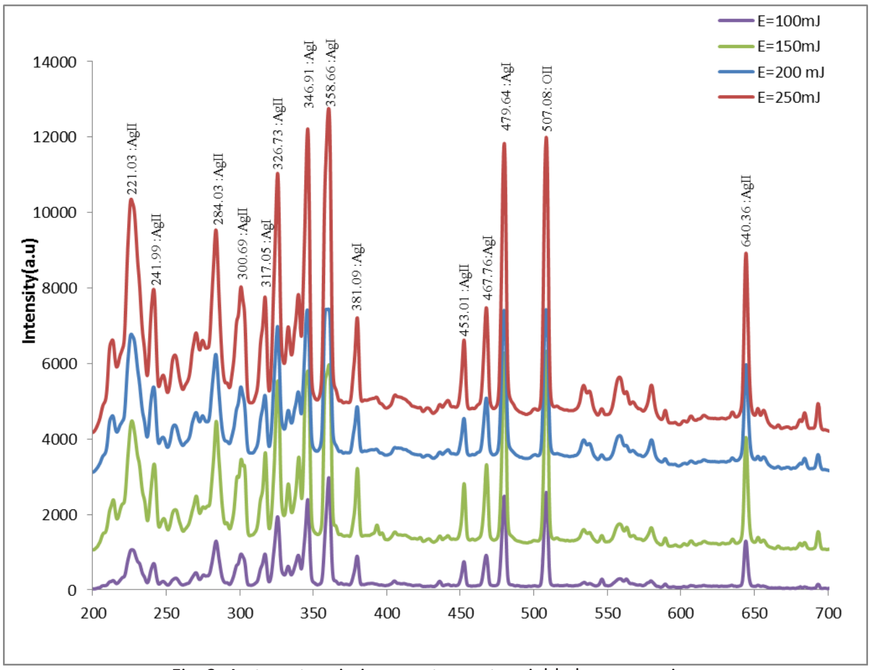

Fig. 2. Ag target emission spectrum at variable laser energies.

environment [8, 9]. The motivation behind this work is to investigate the characteristics of Nd: YAG silver plasma emission. Using the electron temperature and iterative Boltzmann approach will be determined, and the variation of electron temperature and its correlation coefficient with iteration will be studied. Essentially, we examined the spectral properties of atmospheric pressure plasma generated from Ag using a laser with 532 nm a wavelength. The spatial resolution of the optical emission was scanned along its length using a pen-like probe. The electron temperature (T_e) and electron density (n_e) for the spectroscopic study were detected using silver plasma. After analyzing the results obtained, these results are compared with the basic criteria provided by (NIST) also the applied methodologies.

MATERIALS AND METHODS

Fig. 1 presents a schematic diagram of Nd: YAG laser was employed, operating system at a fundamental of 532 nm a wavelength with pulsed duration of 9 ns. The pulsed laser was focused onto silver (Ag) targets in atmospheric air. The (LIBS) setup is illustrated, with laser energies ranging from (100 to 250) mJ used to investigate the plasma properties of the Ag target surface. In the aspect of analyzing plasma emissions, the optical emission spectrometer was used for an accurate diagnostic tool. The spectrometer was positioned 1 cm from the silver target to capture and evaluate key plasma parameters, including electron density (n_e) and electron temperature (T_e). The laser beam was focused using a convex lens with a 100 mm focal length.

RESULT AND DISCUSSION

Fig. 2 presents plasma emission spectral of a silver (Ag) target generated use the interaction of laser pulsed with a silver target under vacuum conditions. The spectrum, covering the wavelength range of 200 –700 nm, consists of distinct spectral lines corresponding to specific atomic and ionic transitions. Emission spectra were recorded using various laser pulse energies: 100, 150, 200, and 250 mJ. The observed wavelengths were matched with standard reference data from the NIST database to accurately identify each spectral line and determine whether it corresponds to a neutral atom or an ion. because laser energies increase, plasma absorbs more of its radiation, and then plasma it becomes more transparent to laser beam, which leads to an increase in radiation and stronger spectral lines [10]. With the laser energy (or intensity) increases, the number of photons hitting the silver surface also increases, leading to the excitation of more electrons from their ground state to higher energy states. These results in an increase in the spectral emission or the signal detected during the process [11]. The increase in spectral intensity is primarily due to enhanced plasma generation and excitation processes rather than surface Plasmon effects.

Briefly, increasing the laser energies led to formation of larger plasma with higher temperatures, accompanied by a moderate increase in electron density. One of fundamental characteristics a laser-excited surface is determining the electron density and their temperature. These parameters are derived based on the thermal and dynamic equilibrium of the thermal level [12]. Collisional processes that induce perturbations in atoms and ions emitted from plasma govern the shape and width of the spectral lines. Accordingly, plasma density can be determined from the linear spectral profile [13]. The spectral constant for the silver temperature estimation lines was obtained from NIST. The emission spectrum generally increases with increasing laser power, as higher power enhances the emission intensity across different wavelengths. However, this relationship depends on the material's properties, the laser wavelength, and the experimental conditions. Table 1 presents the measured and calculated plasma parameters (Debye length λ_D, plasma frequency f_p), electron temperature (T_e), (FWHM), electron density (ne), which meet the plasma criteria. The table shows that the plasma frequency (f_p) and electron density (n_e) increase with increasing laser energy, since f_p is

Table 1. properties plasma for Ag with different energies laser.

Laser energy (mJ)	Te (eV)	FWHM (nm)	$n_e \times 10^{18}$ (cm^{-3})	f_p(Hz)$\times 10^{13}$	$\lambda_D \times 10^{-6}$ (cm)
100	1.053	2.560	2.726	1.483	0.589
150	1.221	2.660	2.832	1.511	0.537
200	1.563	2.815	2.997	1.555	0.488
250	1.952	2.920	3.109	1.583	0.462

directly proportional to ne, while the Debye length (λ_D) decreases with increasing electron density. A high f_p indicates that the plasma becomes denser with high energy.

The Boltzmann plot method was applied using multiple emission lines of the same ionization stage (Ag II) from the silver target, as show in Fig. 3. The required spectroscopic parameters, including upper energy levels, transition probabilities, and statistical weights were obtained from (NIST) database. The electron temperature was determined from the slope of the linear fit of Boltzmann plot, where the slope equal (-1/T). The R^2 value, a statistical indicator of the fit quality, range from 0 to 1, with values closer to 1 indicating a better linear fit. The fitting equations and corresponding R^2 value are provided in the figures for each line, with best fit showing the highest R^2. The absorption of laser energy by plasma at varying intensities can lead to significant electron heating, particularly at high laser powers. This results in enhanced energy deposition within the plasma, causing a substantial rise in electron temperature. This effect becomes especially pronounced in the interactions between high-intensity laser fields and dense plasma environments [14].

The obtained electron density (~ 10^{18} cm^{-3}) together with the measured electron temperature (1.053- 1.952 eV) indicates that the plasma condition satisfies the requirements for local thermodynamic equilibrium, thereby validating the application of the Boltzmann plot method in the present analysis.

The research findings clearly show that laser intensity directly affects the electron density in the plasma. As laser power increases, the material undergoes stronger interactions, leading to higher ionization and electron generation. Consequently, greater laser power typically results in higher electron density. As shown in Fig. 4, when the laser energies increase at a fixed wavelength of 532 nanometers, the beam becomes practically plasma shielding, as the laser beam protecting the target becomes opaque due to the plasma. The

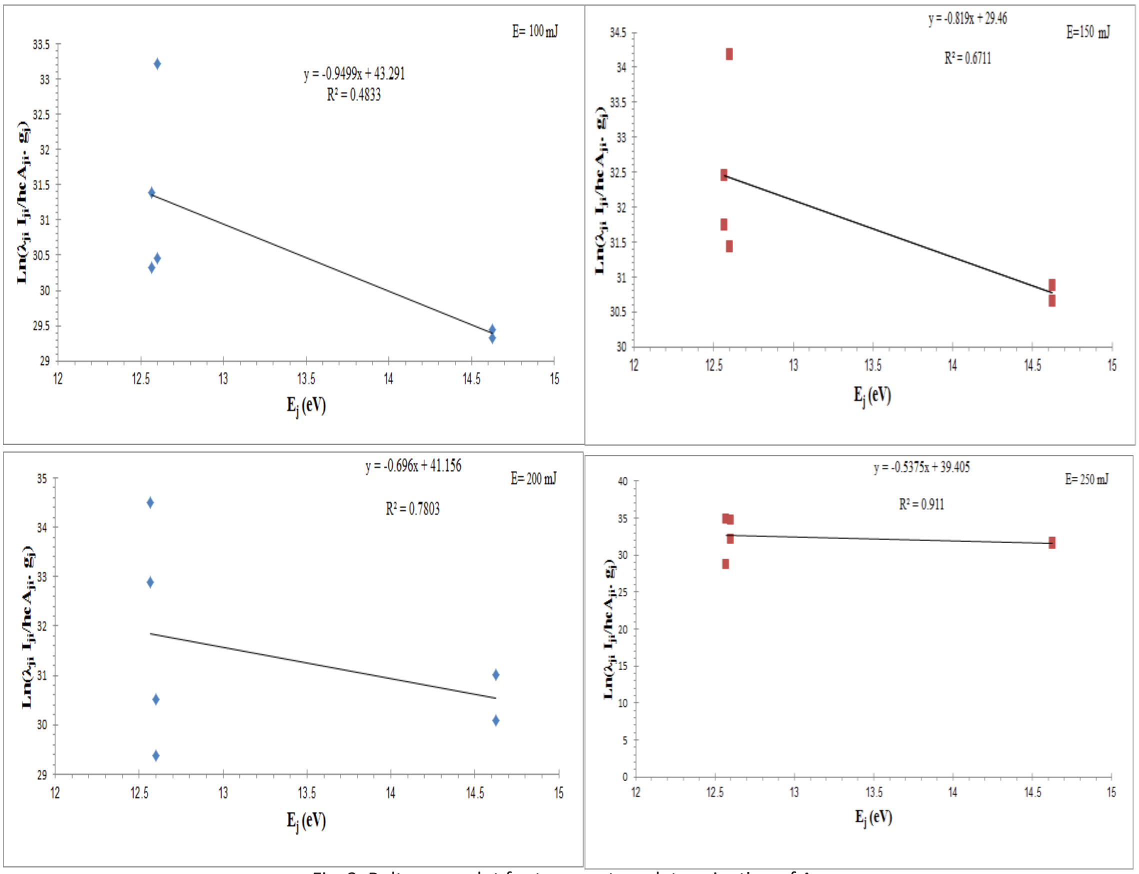

Fig. 3. Boltzmann plot for temperature determination of Ag.

plasma reduces the transmission of laser energies used along beam's own path [15, 16].

Fig. 5 shows the effect of different laser energies at wavelength 532 nm on the plasma frequency and Debye length in the silver plasma spectrum. As the laser energy increases from approximately 100 mJ to 250 mJ, we observe a significant rise in plasma frequency (f_p), indicating a corresponding increase in electron density within the plasma. Higher laser energy leads to enhanced electron

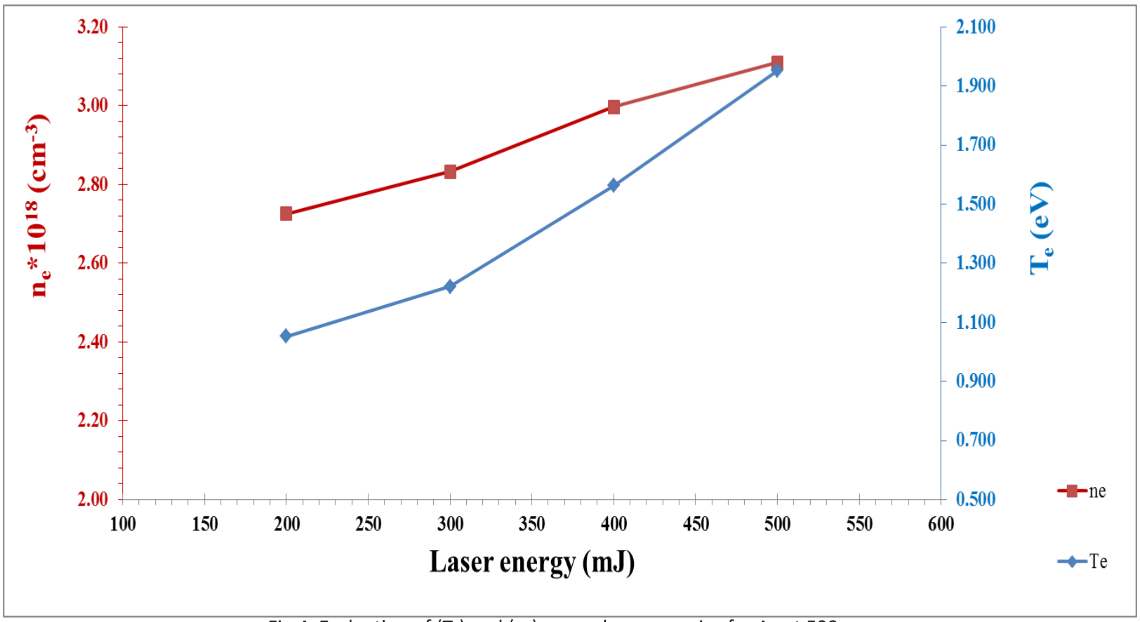

Fig.4. Evaluation of (T_e) and (n_e) versus laser energies for Ag at 532nm.

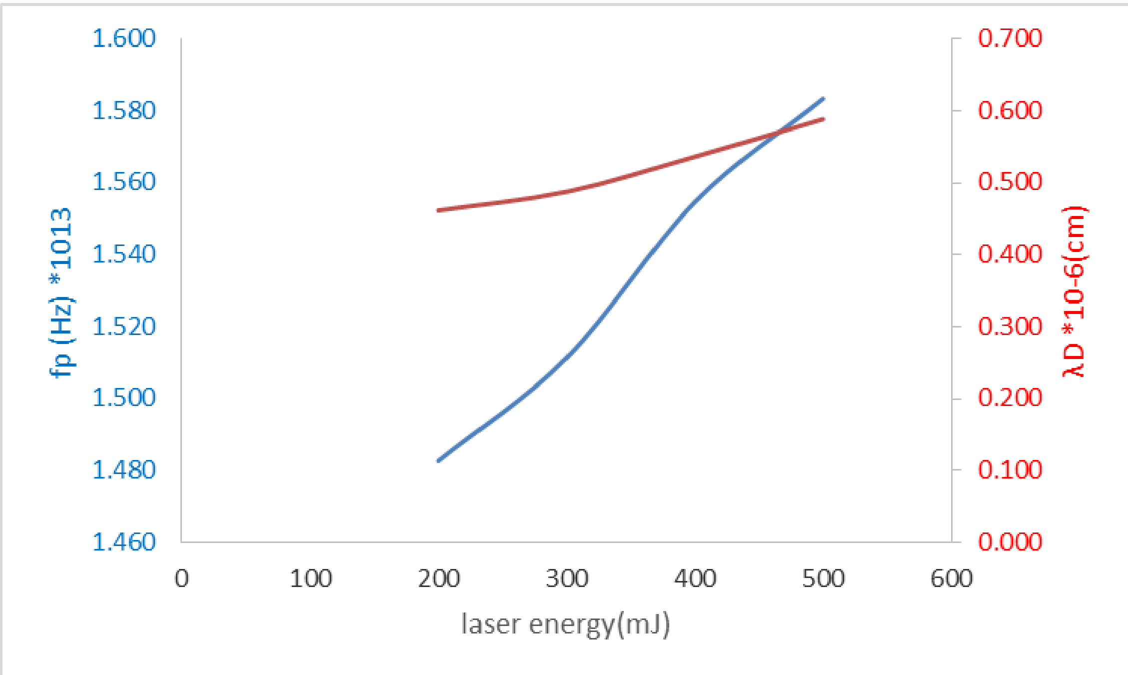

Fig. 5. Shows the effect of different laser energies on the plasma frequency and Debye length in Ag plasma.

excitation and emission. Meanwhile, the Debye length (λ_D) decreases with increasing laser energy due to the increase in electron density, which reduces the effective shielding length in the plasma. This decrease indicates that the spatial range over which electric charges influence each other become more limited [17, 18].

CONCLUSION

The intensity of spectral line prepared at a wavelength of 532 nanometers for laser-induced plasma emission under different laser energies showed a strong dependence on the surrounding conditions. The interaction of laser energies with the used metallic target, silver, is a highly effective method for producing plasma parameters consisting of electrons, neutral particles, and ions. It was found that the plasma spectrum induced by different laser energies exhibits strong spectral line, and there is an increase in their intensity with increasing laser energies. It was also observed that the plasma parameters are affected by the increase in laser energies at a wavelength of 532 nm.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript.

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