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Spectroscopic Diagnosis of the CdO:CoO Plasma Produced by Nd:YAG Laser

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Abstract

In this paper, the optical emission spectrum (OES) technique was used to analyze the spectrum resulting from the (CdO:CoO) plasma in air, produced by Nd:YAG laser with $\lambda=1064$ nm, $\tau=10$ ns, a focal length of 10 cm, and a range of energy of 200-500 mJ. We identified laser-induced plasma parameters such as electron temperature (T_e) using Boltzmann plot method, density of electron (n_e), length of Debye (λ_D), frequency of plasma (f_p), and number of Debye (N_D), using two-Line-Ratio method. At a mixing ratio of $X=0.5$, the (CdO:CoO) plasma spectrum was recorded for different energies. The results of plasma parameters caused by laser showed that, with the increase in laser energy, the values of T_e , n_e and f_p were increased, while the value of λ_D was decreased. The calculated electron temperature value was in the range of 0.449-0.619 eV at ratio $X=0.5$

Keywords: Optical Emission Spectroscopy (OES), Laser Induced Plasma Spectroscopy, Cadmium Oxide (CdO), Cobalt Oxide (CoO), Nd:YAG laser.

التشخيص الطيفي لبلازما اوكسيد الكاديوم المشوبة بأوكسيد الكوبالت المنتجة بواسطة ليزر Nd:YAG

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الخلاصة

في هذا البحث تم استخدام تقنية مطياف الانبعاث البصري والذي يعمل على التقاط الطيف الناتج من البلازما (CdO:CoO) المنتجة باستخدام ليزر (Nd: YAG) ذو الطول الموجي (1064) نانومتر، والمدة الزمنية (10) نانوثانية، و طول بؤري (10) سانتيمتر، في نطاق الطاقة (200-500) ملي جول، تم حساب معاملات البلازما مثل درجة الحرارة (T_e) باستخدام طريقة بولتزمان-بلوت. بينما تم حساب كثافة الالكترون (n_e)، وطول كرة ديبي (λ_D)، وتردد البلازما (f_p) وكذلك عدد الجسيمات في كرة ديبي (N_D) باستخدام طريقة شدة نسبة خطين طيفيين تم تسجيل الطيف الناتج من البلازما مع قيم مختلفة من الطاقة باستخدام مزيج من اوكسيد الكاديوم CdO المشوب بأوكسيد الكوبالت CoO بنسبة مئوية عند ($X=0.5$). وقد أظهرت نتائج معاملات البلازما الناتجة عن الليزر ان قيم (T_e), (n_e), (f_p) قد زادت مع زيادة الطاقة بينما أنخفضت قيمة (λ_D) مع زيادة الطاقة، وكانت قيمة حساب درجة حرارة الالكترون الناتجة تتراوح ما بين (0,619-0,449) الكترون فولت عند نسبة ($X=0.5$).

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1. Introduction

Laser-Induced Plasma Spectroscopy (LIPS) is considered to be a proven analytical method used for the rapid determination of sample elemental composition. LIPS can also be characterized as a type of atomic emission spectroscopic analytical technique that can be used to analyze any type of matter, whether in a liquid, solid or gaseous state [1]. In LIPS, plasma produced at laser beam concentrated on the surface of a target excites and ionizes the target material. The plasma is emitting from the target's surface material directly after the laser beams' photons hitting the surface. By analyzing the emission spectra from laser-induced plasma, optical detection of certain atomic and molecular species is obtained. The analytical efficiency of LIPS is highly influenced by the chosen experimental conditions and parameters such as laser light wavelength, laser pulse energy, pulse duration, observation time duration, ambient gas pressure, target type and properties, and the geometric configuration of the optical instruments [2]. Atomic components emit distinctive light that can be observed using optical fibers and sent to the spectrometer for analysis [3]. Recently, Optical Emission Spectroscopy (OES) has obtained a great deal of consideration for the depiction that is dependent on LIPS [4]. Plasma is created as the energy from the laser pulse heats, ablates, atomizes, and ionizes the sample material. The plasma plume is then spectrally observed and analyzed by a spectrograph and a detector. It is possible to deduce from the resulting plasma spectrum both quantitative and qualitative information, such as elemental composition. Properties of the emission line, such as widths, shapes, and changes, may provide plasma temperature and electron density details [5]. One of the most common techniques for the OES is the Ratio method uses in this research, while one of the best techniques for measuring the electron temperature in the local thermodynamic equilibrium is the Boltzmann plot equation [6], expressed as follows:

$$\ln \left[\frac{\lambda_{ji} I_{ji}}{hc A_{ji} g_j} \right] = \frac{1}{k_B T} (E_j) + \ln \left[\frac{N}{U(T)} \right] \quad \dots \dots \dots (1)$$

Where I_{ji} is the relative emission line density between energy levels I and j.

g_j is the degeneracy or the upper level statistical weight emitted from the transition phase.

λ_{ji} is the wavelength (in nano metres).

E_j is the excitation energy (in eV) for level j.

A_{ji} is the possibility of automatic transmission of radiation from the level i to the lower level j .

N is the density of the population of the state. k_B is the constant of Boltzmann.

The electrical field induces laser-induced plasma to have Stark effects, mainly from electron collisions, with small contributions due to collisions with ions. The equation can be simplified as [7]:

$$n_e = \left(\frac{\Delta\lambda_{FWHM}}{2\omega} \right) N_r \dots \dots \dots (2)$$

where $\Delta\lambda_{FWHM}$ is the full width of the spectral line at half maximum,

ω is the theoretical line of full-width of the Stark parameter for broadening, calculated at the same reference electron density, $N_r \approx 10^{17} \text{ cm}^{-3}$.

While the frequency of plasma is defined such that any disturbance from quasi-neutral equilibrium in the plasma will create electric fields. This frequency, which only depends on the density of the plasma, is one of the most important plasma parameters. Due to the smallness of m, the plasma frequency is usually very high, which is calculated by the equation below [8].

$$f_p = \sqrt{\frac{e^2 n_e}{\epsilon_0 m_e}} \dots \dots \dots (3)$$

Where ϵ_0 is the permittivity of the free space, e is the charge of the electron, n_e is the density of the number, and m_e is the mass of the electron. The length of Debye (λ_D) is the fundamental characteristic of the behavior of plasma, as it describes the distance in which the individual particle affects another charged particle that carries a reverse charge inside the medium of the plasma. The length of Debye is directly proportional to the square root of the temperature of the electron and inversely proportional to the electron density, according to [9].

$$\lambda_D = \sqrt{\left(\frac{\epsilon_0 k_B T_e}{n_e e^2} \right)} = 7430 * \sqrt{\frac{T_e}{n_e}} \dots \dots \dots (4)$$

Where k_B is the constant of Boltzmann, λ_D is the length of Debye (cm),

L is the system dimension (cm), n_e is the electron's density (cm^{-3}),

(T_e) is the electron's temperature (eV), and e is the electron's charge (C).

Debye length should be very small when this first condition for plasma existence is compared to the system dimension ($\lambda_D \ll L$) [10]. In Debye's sphere, the number of particles (N_D) is dependent on the electron density and electron temperature and it represents a second condition for plasma existence ($N_D \gg 1$), as follows [11]:

$$N_D = \frac{4}{3} \pi n_e \lambda_D^3 \dots \dots \dots (5)$$

The main objective of this paper is to use spectral emission of light to study plasma parameters using spectral lines emitted from (CdO: CoO) pure atoms surrounding the plasma.

2. Experimental Part

In this experiment, the plasma was produced using a pulsed laser on a solid target (CdO: CoO). The experimental arrangement of LIPS is shown in Figure-1. A pulse laser (Nd: YAG) with a wavelength of 1064 nm and a frequency of 6 Hz was used to generate the plasma. The target material laser beam was concentrated on the target, making an angle of (45 °) with it. The target material was evaporated and ionized by a laser beam, creating a plasma plume above the target surface. The technique of OES was used for determining the electron's temperature, densities, and plasma frequency. The length of the Debye and Debye number were determined mathematically. The spectrometer that is commonly used must be fast with the same response time in every shot. Thus, Surwit (S3000-UV-NIR) spectrometer was used in the setup to determine emission wavelengths and has high-efficiency goals. A wavelength range of (300-800) nm was obtained for each spectrum. The plasma spectrum with different energy values was prepared by mixing CdO with CoO at X= 0.5, while the laser pulse energy varied from 200 to 500 mJ. The findings were discussed and compared with the National Institution of Standards and Technology (NIST) database [12], as shown in Table-1.

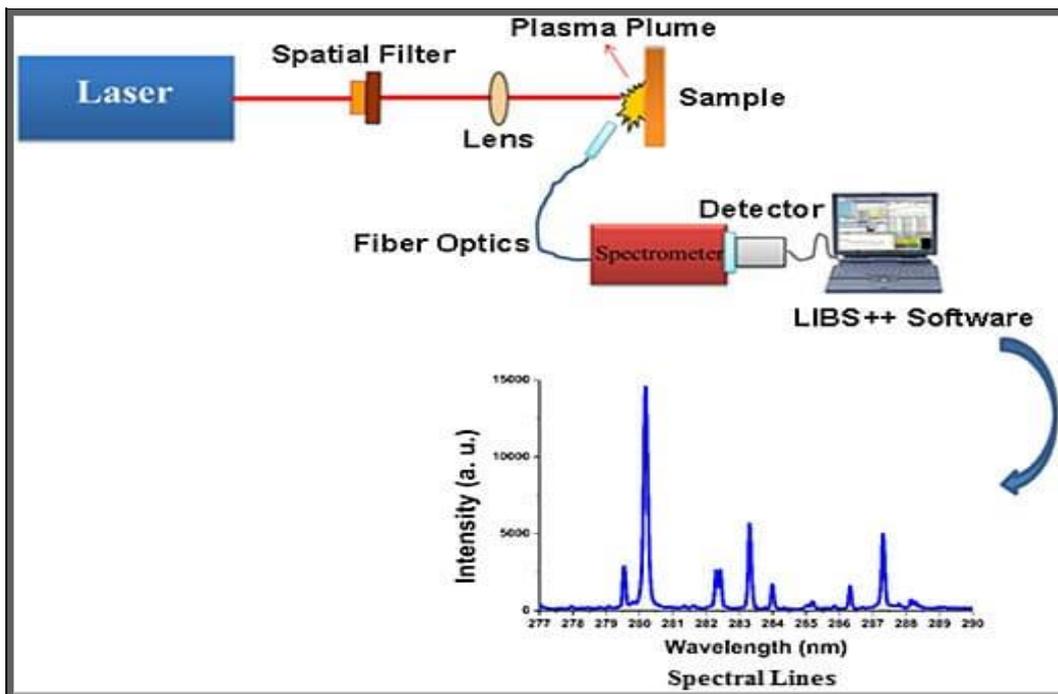


Figure 1- Laser Induced Plasma Spectroscopy (LIPS) system configuration

Table 1- Spectroscopy parameters of CdO:CoO plasma.

Elements	λ (nm)	$g_k A_{ki} (s^{-1})$	$E_k (eV)$
Cd II	366.6	1.6×10^6	14.5
	382.6	2×10^5	13.605
	537.8	4.6×10^6	13.443

3. Results and Discussion

Evaporation and ionization of the target material by the laser beam generates a plasma plume over the target's surface. The plasma resulting from the laser beams' interaction with the target material's surface includes electrons and ions in an excited state, in addition to neutral atoms and radiation. The

optical emission spectra of the CdO:CoO plasma were recorded using an OES technique with Nd-YAG laser ($\lambda=1064$ nm). Figure-2 show the spectroscopic patterns for laser-induced on the CdO:CoO component at X= 0.5 percentages of target plasma of the target's plasma confined in the air in the spectral range of (300-800) nm with E=(200-500) mJ. These results reveal that the intensity increases with increasing laser energy [13].

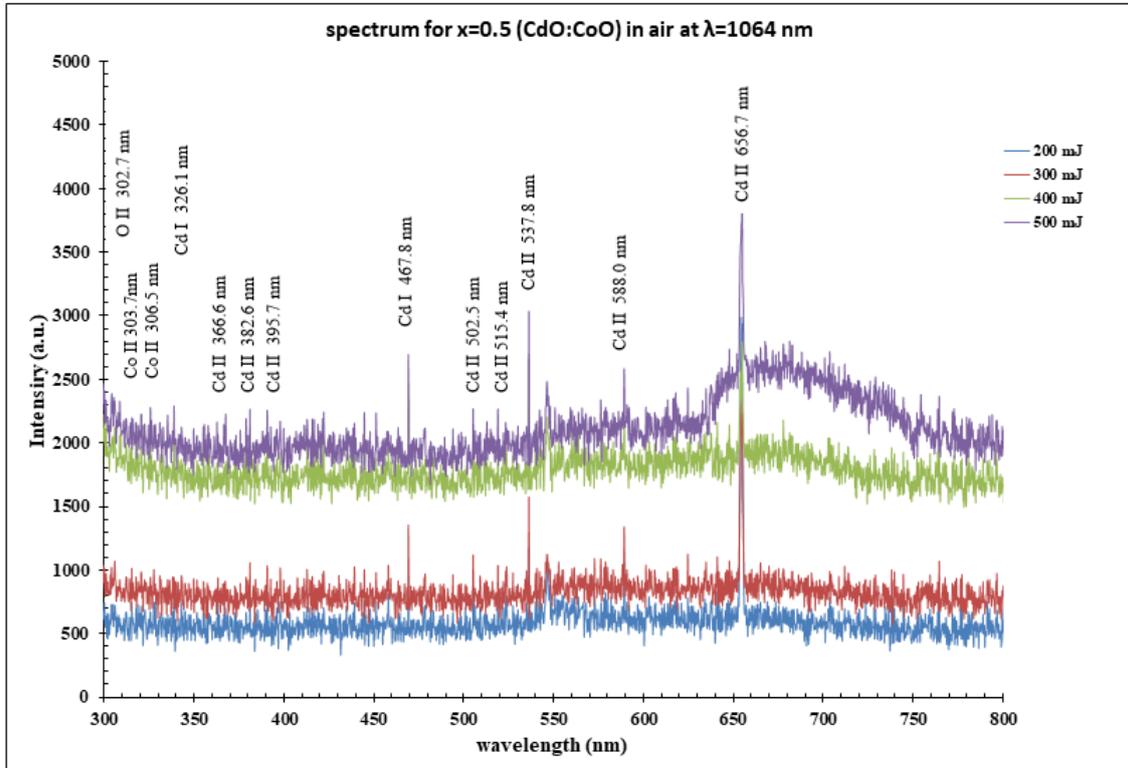


Figure 2- Emission spectra of laser-induced on CdO:CoO component at X=0.5 target in the air with different laser energies.

The process of plasma analysis was performed by measuring the parameters of T_e and n_e . The knowledge of the plasma temperature and density of the plasma species is important for understanding the atomic ionization and excitation processes occurring inside the plasma. This is achieved by applying the straight line equation with a gradient of $-1/k_B T$. If one plots a graph of $\ln \left[\frac{\lambda_{ji} I_{ji}}{h c A_{ji} g_j} \right]$ versus E_j for several simultaneously measured emission lines, the plasma temperature can be determined. R^2 is a statistical coefficient indicating the quality of the linearity .

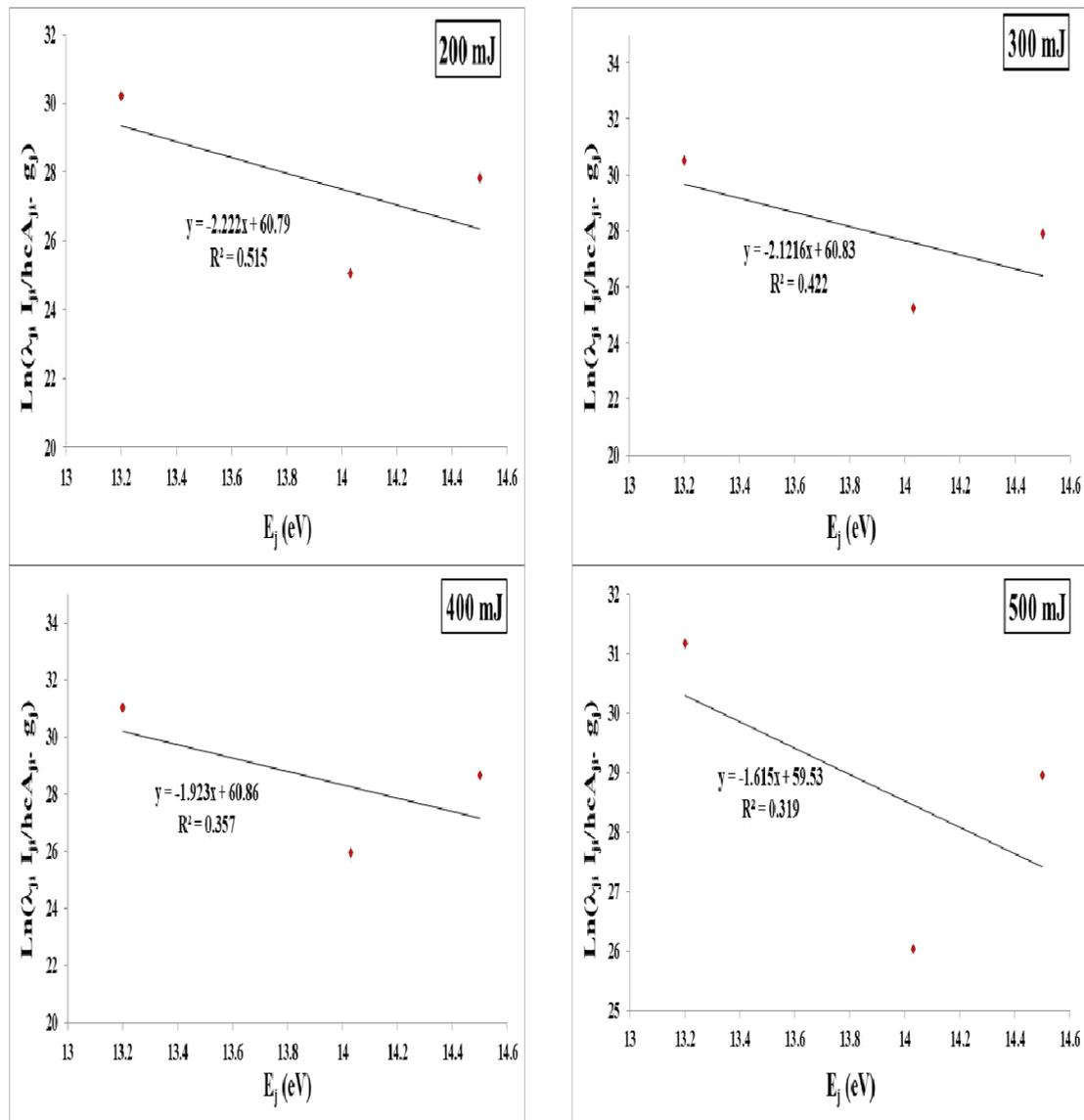


Figure 3- Boltzmann plot of plasma emission for CdO:CoO target at different laser energy values.

Table-2 shows the data of the electron temperature (T_e), electron density (n_e), Debye length (λ_D), the plasma frequency (f_p) and the Debye's number (N_D) for CdO:CoO target at X=0.5 and different laser energy values. Criteria for the plasma were achieved through the results of the plasma parameters (λ_D , f_p and N_D). It shows that N_D , f_p increase with increase laser energy because it is proportional with n_e , while λ_D are decreased.

Table 2- Plasma parameters for CdO:CoO at X=0.5 with different laser energies.

Laser energy (mJ)	T_e (eV)	$n_e \times 10^{17}$ (cm^{-3})	$\lambda_D \times 10^{-5}$ (cm)	$N_D \times 10^3$	$f_p \times 10^{12}$ (Hz)
200	0.449	7.5	0.649	0.858	7.777
300	0.471	11.4	0.567	0.871	9.588
400	0.519	18.75	0.559	1.371	12.296
500	0.619	22.5	0.447	2.551	13.470

We calculated T_e values from the Boltzmann plot by using Eq. (1). The values of electron's temperature and electron's density were increased by increasing the laser pulse energy, as shown in Figure-3. T_e becomes almost stable at higher laser peak energy, because the plasma appears opaque to the laser beam which shields the target. Plasma shielding occurs when the laser transmission occurs.

The plasma itself reduces peak power along the beam path. The reason for these increases is that the laser peak energy has a strong and important effect on the emission lines' intensities. As the intensities of the spectral lines increase, the laser peak intensity increases as the target's mass ablation rate also increases. The increase in laser energy will also increase its absorption in the plasma, resulting in more ablation, which leads to increasing the number of excited atoms and thus, the intensities of the peaks of a spectral line of plasma emission [14].

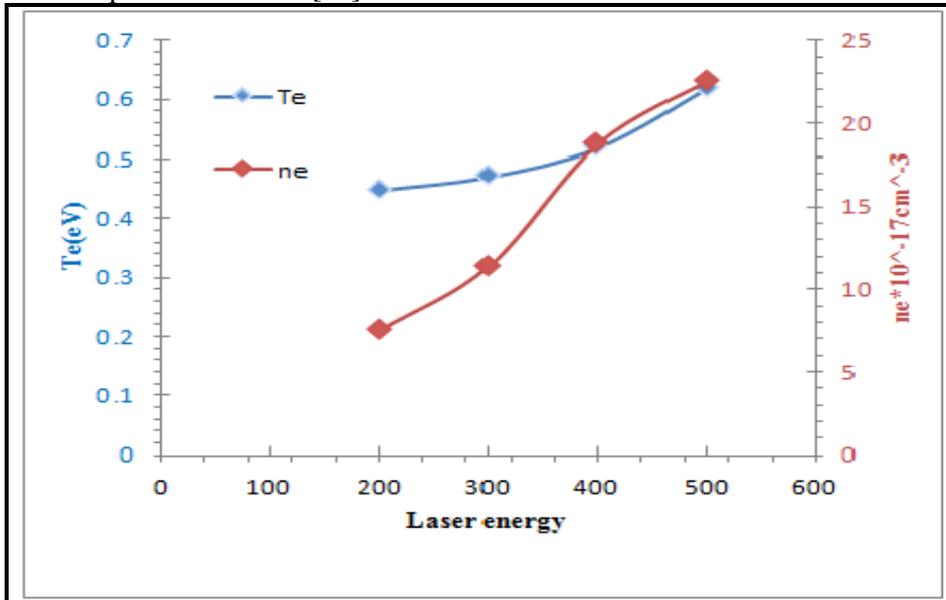


Figure 4- The variation between T_e and n_e versus the laser energy for CdO:CoO at X=0.5 with different energy values.

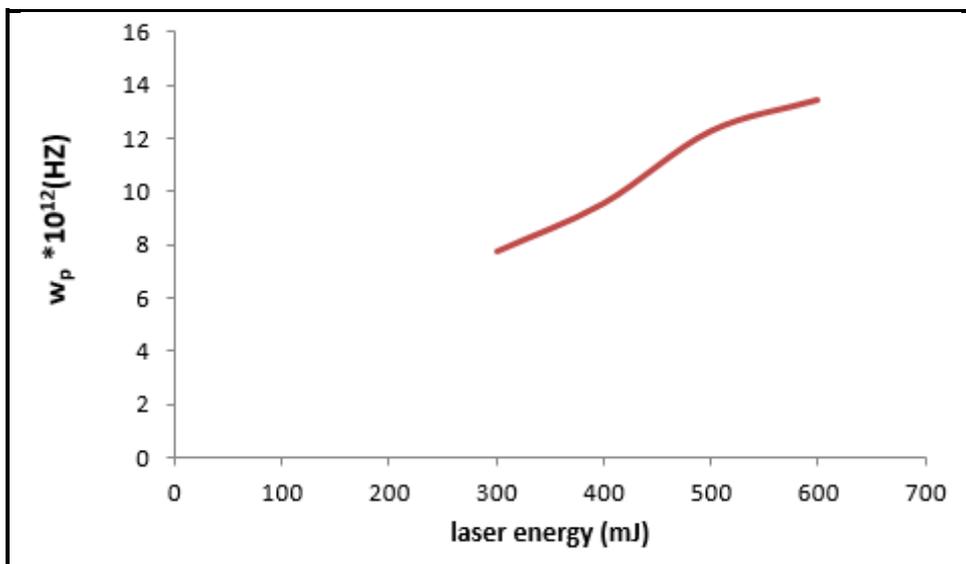


Figure 5- Variation of the plasma frequency for CdO:CoO at X=0.5 with different laser energy values.

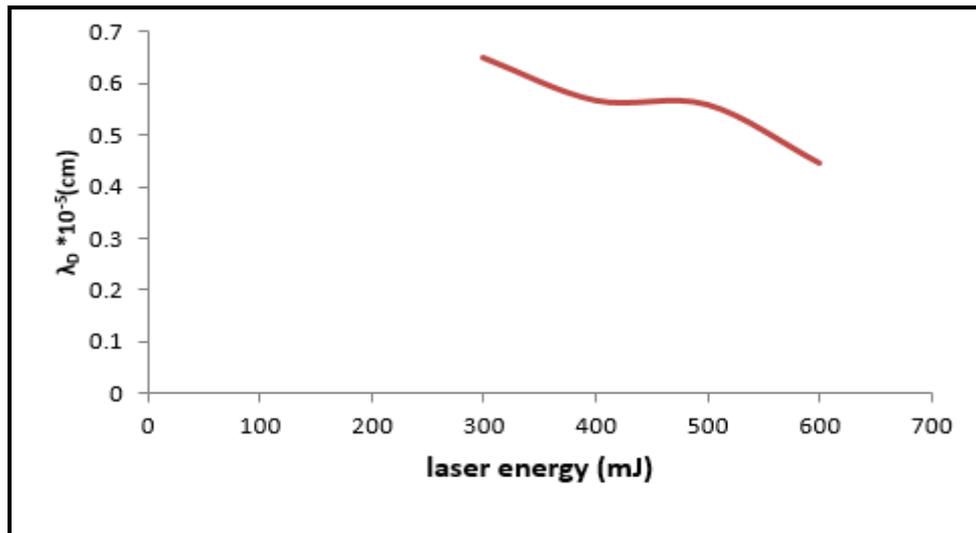


Figure 6- Variation of the Debye's length for CdO:CoO at X=0.5 with different laser energy values.

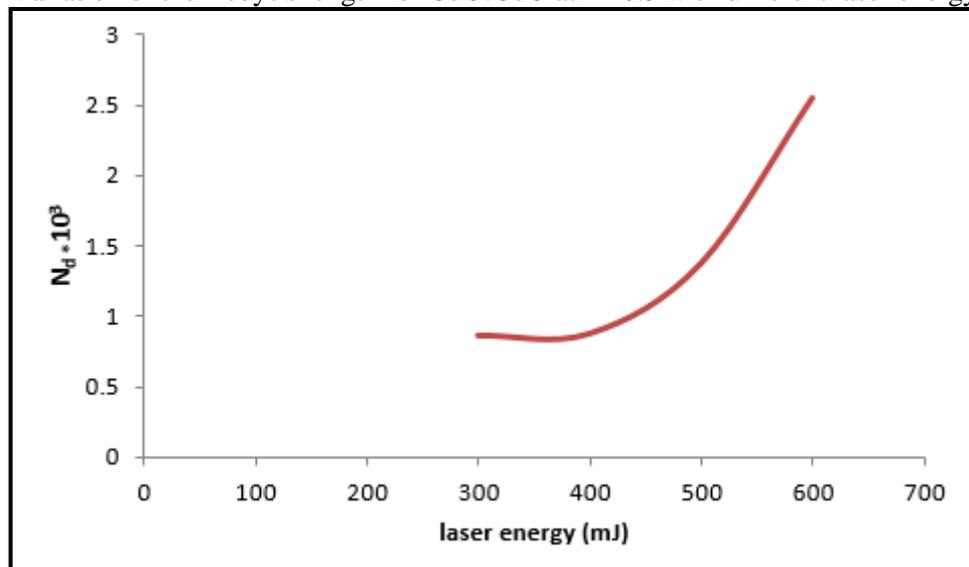


Figure 7- Variation of the Debye's sphere for CdO:CoO at X=0.5 with different laser energy values.

4. Conclusions

Plasma CdO: CoO was produced using an Nd: YAG laser with a wavelength of 1064 nm at different energies of 200 - 500 mJ. Optical emission spectroscopic studies were performed to determine the measurement of plasma parameters, such as the electron's density and the electron's temperature. The plasma parameters were estimated in terms of their dependence on the laser energy. The results indicated that the values of T_e , n_e , N_D and f_p were increased with increase laser energy, while the value of λ_D was decreased.

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