Control of plasma parameters and spectral analysis sensitivity under bichromatic laser irradiation of materials in gases

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Abstract. Double-pulse nanosecond bichromatic laser irradiation of carbon and brass targets is implemented. The dependence of temperature and density of electrons, as well as the specific recoil momentum of an outflowing plasma jet, on the ordering of laser pulses and the inter-pulse time delay is found. The results obtained can be used for the development of laser-plasma spacecraft microengines and the enhancement of laser spectral analysis’ sensitivity.

1. Introduction
It is known that multi-pulse and double-pulse modes of laser exposure are more effective for local spectral analysis and for making the spacecraft laser-plasma engines as compared to single-pulse mode [1-7]. It was found that the double-pulse laser irradiation (LI) intensifies the rate of heating the targets’ vapors within a certain range of time intervals between the pulses [2, 3, 7]. Furthermore, the hole drilling under laser pulses train action [4] and the laser-induced breakdown spectroscopy [5] were found out to be more efficient for these modes. Additional benefits in formation and heating of laser plasmas can be achieved by the double-pulse mode of the material irradiation at different wavelengths due to the dependence of the targets reflectance and radiation absorption of plasma on the wavelength of the LI.

2. Experimental setup
The double-pulse LI was produced by synchronizing two Nd:YAG lasers with wavelengths of 1064 and 532 nm \(E = 100 \text{ mJ}, \tau = 20 \text{ ns}\) with adjustable time interval between laser pulses. The dependence of electron density and temperature of the plasma on the ordering of laser pulses and the inter-pulse time delay during laser exposure of various materials in air was studied. The most representative data were obtained using the brass and graphite targets.

In these experiments, the radiation emission spectra of a near-surface plasma and the pressure pulses on the irradiated targets were registered. The SDH-IV spectrometer with exposure time of 7 ms was used for spectral registration of laser plasma. The spectrometer was equipped with a linear CCD detector TCD 1304 AP (Toshiba) connected to a computer and a laser system synchronization unit. For registration of pressure pulses on the target and of the LI pulses, a piezoelectric detector synchronized with the Bordo 221 digital oscilloscope was used. Recoil momenta for different materials were determined by integrating the pressure signal over time.

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3. Results and discussions
The structure of laser plasma plume and the spectra under the double-pulse LI of a brass target is presented in figure 1. Figure 1a shows the images of the brass plasma plume for different ordering of pulses and various time intervals between them. The photographs served as a basis for estimating the characteristic size of the luminous area of the laser plume, which varies from 8.5 to 11 mm depending on the ordering of laser pulses and the time intervals between them. In figure 1, the negative values of intervals between laser pulses correspond to the target’s irradiation starting with the shortwave laser (λ=532 nm), and the positive ones correspond to a start with the longwave laser (λ = 1064 nm).

![Figure 1. Structure of laser plasma plume (a) and its radiation emission spectra (b) under laser irradiation of the brass in various irradiation modes.](image)

The obtained spectra enabled us to determine the electron temperature $T_e$ in the near-surface laser plasma from the relative intensities of spectral lines, and the density of electrons $n_e$ from the Stark broadening of hydrogen and carbon spectral lines. The experiments were conducted at the LI power density $q_{0.532} = q_{1.064} \leq 4 \times 10^8 W/cm^2$ in a laser spot of diameter $d_p = 0.30 \text{ mm}$. It was found out that the exposure to shortwave LI stimulates the formation of an erosion-produced plasma while the infrared LI produces predominantly an air plasma. The experimental results showed that the parameters of laser-produced plasma on the brass and graphite targets depend on the ordering of laser pulses and the time interval between them. In the experiments with brass, the maxima of plasma temperature ($24 \times 10^3 K$) and electron density ($4.5 \times 10^{17} \text{ cm}^{-3}$) are attained in the case of outrunning shortwave irradiation at $\lambda = 532 \text{ nm}$, but at different values of the time interval between laser pulses, $\Delta t = -5 \mu s$ and $\Delta t = -1.5 \mu s$, respectively.

In the experiments with graphite the spectral lines N II 399.5 nm and the group of lines N II (499.4 nm – 500.7 nm) were used to determine the plasma temperature (figure 2a), while electron density was evaluated from the measurements of the broadening of carbon spectral lines C II 426.7 nm (figure 2b). The maxima of plasma temperature ($18 \times 10^3 K$) and electron density ($4.7 \times 10^{17} \text{ cm}^{-3}$) are attained in the case of outrunning shortwave irradiation at $\lambda = 532 \text{ nm}$, but for different time intervals between laser pulses, $\Delta t = -2.5 \mu s$ and $\Delta t = -1.5 \mu s$, respectively. The differences of the values of inter-pulse time interval, which correspond to the maximum temperature and plasma density, can be explained by the complexity of the spatial structure of a dynamic plasma.
Figure 2. Dependence of temperature (a) and electron density (b) in the carbon plasma on the time interval between laser pulses.

Figure 3. Dependence of the measured (1) and calculated (2) recoil momentum on the time interval between laser pulses for the plasma on the brass (a) and graphite (b) targets.

This happens essentially due to a higher absorbing ability of the target and accumulation of erosive vapors under the influence of initial pulse with a shorter wavelength, as well as due to a quadratic dependence of the absorbing ability of plasma plume on a longer wavelength of the second acting laser pulse. Experimental dependencies of recoil momentum on the time interval between laser pulses are in satisfactory agreement with the estimates obtained using the equation of state for ideal gas and the value of laser pulse duration (figure 3a – for brass, figure 3b – for graphite). On the basis of obtained parameters and spatial structure of the plasma, it can be concluded that the most compact form of the plasma plume with the minimal expansion into the surrounding environment corresponds to maximum values of its parameters: plasma temperature, charged particle density and specific recoil momentum.

4. Conclusion
In this paper, we report on the dependencies of temperature, charged particle density and recoil momentum of a laser-produced plasma on the ordering of the double-pulse laser irradiation of the brass and graphite targets in air at wavelengths of 1064 and 532 nm and on the time interval between pulses. The characteristic size of radiation emission area of the plasma torch was determined using the
photographic recording of a laser torch on a brass target in air for different modes of bichromatic laser irradiation. It was shown that the optimal conditions for recording the spectra of erosion-produced plasma of brass and graphite are provided in the case of outrunning shortwave laser irradiation at $\lambda = 532$ nm with the time interval between the pulses within 3-6 $\mu$s range. As for generation of the recoil momentum, the optimum time interval is 1.5-2 $\mu$s. These experimental results are essential for the enhancement of the sensitivity of laser spectral analysis and of the efficiency of laser plasma microengines.

References

[1] Minko L Ya, Chumakov A N and Bosak N A 1990 Sov. J. Quantum Electronics 17 1480
[2] Minko L Ya, Chumakov A N and Bacanovich G I 1994 Journal of Applied Spectroscopy 61 476
[3] Petuh M L, Rozantsev V A, Shirokanov A D and Jankowski A A 2000 Journal of Applied Spectroscopy 67 798
[4] Pershin S M 2009 Quantum Electronics 39 63
[5] Cremers D and Radziemski L 2009 Laser-induced breakdown spectroscopy (Moscow: Technosphere) 360
[6] Lubchenko F N, Fedenev A V, Bosak N A, Chumakov A N, Panchenko A N and Tarasenko V F 2009 Cosmonautics and Rocket Engineering 3 62
[7] Chumakov A N, Avramenko V B and Bosak N A 2012 Journal of Applied Spectroscopy 79 279-287