CCD camera-based diagnostics of optically dense pulsed plasma with account of self-absorption

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Abstract. We present a system developed for the optically dense pulsed plasma diagnostics based on a digital video camera with a CCD matrix, that provides determination of spectral brightness and optical density with account of self-absorption.

1. Introduction

Real sources of a pulsed plasma (lasers, discharges, etc.) are often not optically thin, so the diagnostics of such plasmas should be performed taking into account the reabsorption of the radiation in the investigated source [1]. Plasma self-raying by its own radiation [2, 3], or by the radiation from an external source [4] can be used to determine the optical density and spectral absorption coefficients of the investigated plasma. The special scheme of self-raying, that provides spectral transmission factors with a resolution in any dimension of the source in a single experiment in combination with the spectrograph allows determining the temperature and transmission factors of plasma [3]. We used this scheme to create a prototype of a diagnostic system for measuring the spectral brightness and optical density of a pulsed plasma with a CCD digital video camera. This allows improving the accuracy of measurements, minimizing the size of the experimental setup, as well as speeding up and simplifying the data recording and processing.

2. Experimental details and analysis

The prototype of the diagnostic system schematically shown in figure 1 consists of a plasma self-raying device and optical radiation registration system based on the SONY ICX415AL CCD image sensor. A special mask 2 is a lattice with uniformly positioned slits, made of a material that absorbs optical radiation, placed on the surface of the concave spherical mirror 1 of the self-raying device. The plasma source 5 generates the plasma torch 4. The objective lens 3 projects an image of the torch to the mirror 1. The radiation reflected from the mirror allows the lens to form the real image of the plasma source, that coincides with the original image. The objective lens 7 projects the image of the plasma torch through the system of optical filters 6, 8 on the CCD 9. The “CCDImage” software is used for setting the registration parameters, saving and exporting the results in various formats for further data processing.
Figure 1. Optical self-ray diagnostic system. 1 – concave spherical mirror; 2 – mask; 3 – objective lens; 4 – plasma torch; 5 – plasma source; 6-9 – digital video camera (6 – neutral filters set; 7 – objective lens; 8 – narrow-band filter; 9 – optical registration system based on the CCD Image Sensor SONY ICX415AL); 10 – computer.

The intensity distribution of the plasma torch registered by the diagnostic system has the following form: the amplitude of the signal from the plasma object is registered at the position of the absorbing strips of the mask, and the amplitude of the signal from the self-rayed plasma can be estimated between these strips (figure 2).

Figure 2. The configuration of the mask (a). The intensity distribution (2D (b) and 3D (c)) of the self-rayed plasma radiation, using the hydrocarbon burner flame as an example.

Digital camera based on the SONY ICX415AL CCD array was equipped with narrow-band and neutral filters and calibrated according to the spectral radiance of the SI10-300u photometric lamp metrologically certificated in the 0.3 - 2.5 \( \mu \text{m} \) range [5]. The SIP-30 stabilized DC unit was used as a lamp power supply. The current was measured with the M-104 ammeter.

The spectral brightness of plasma can be found using the spectral radiance of the reference radiation source and registration conditions (exposure and the plasma glow time, aperture, shooting distance and transmittances of filters) [5]:

\[
B_1 = B_2 \frac{\Omega_2}{\Omega_1} \frac{S_2}{S_1} \frac{\tau_2}{\tau_1} \frac{I_1}{I_2}
\]
where $B$ is the spectral brightness (1 – plasma, 2 – reference source), $S$ is the cross-section of the radiation source, $\Omega$ is the solid angle, $\tau$ is the transmission coefficient of the set of filters and $I$ is the signal amplitude.

Assuming that the solid angle and the cross-section of the radiation source are given by

$$\Omega = \frac{\pi f^2}{4 D^2 \cdot L^2}$$

and

$$S = K^2 \cdot d_{\text{pixel}}^2$$

formula (1) (when using the same lens) becomes

$$B_1 = B_2 \frac{D_1^2 L_1^2 \tau_2 \Delta t_2 K_2^2 I_1}{D_2^2 L_2^2 \tau_1 \Delta t_1 K_1^2 I_2}$$  \hspace{1cm} (2)$$

where $B$ is the spectral brightness (1 – plasma, 2 – reference source), $D$ is the f-number (the ratio of the lens's focal length to the diameter of the entrance pupil), $L$ is the distance from the lens to the object, $\tau$ is the transmission coefficient of the set of filters, $\Delta t$ is the exposure time, $K$ is the magnification of the optical registration system, and $I$ is the signal amplitude.

Figure 3 shows examples of optical characteristics determination of the plasma torch formed by the free-running Nd:YAG laser ($\lambda = 1064$ nm, $\tau = 200$ µs, pulse energy up to 1 J, beam diameter of 8 mm) irradiation of a structural steel target.

The transmission coefficient of the optical system is given by:

$$B_1/B_1' = 1 + \rho \lambda \tau$$  \hspace{1cm} (3)$$

where $B_1$ is the brightness of the radiation of the plasma torch, $B_1'$ is the brightness of the plasma radiation, enhanced by the reflected beam, $\rho$ is the transmittance of the optical scheme based on the calibration, $\tau$ is the transmittance of the plasma ($B_1$ and $B_1'$ are calculated by the formula (2)).

Using (3) we can derive the transmittance, and then the optical density and the absorption coefficients of the plasma. The obtained values of spectral radiance of the plasma source can be used not only to calculate its radiance temperature, but also to assess the actual temperature on the basis of the obtained absorption coefficients of the plasma and the use of the Kirchhoff’s law.

Test experiments with the plasma torch formed by the Nd:YAG laser irradiation of targets made of different materials, showed that equipping a digital camera calibrated to the absolute value of the radiance in narrow spectral intervals with the plasma self-raying device significantly enhances the diagnostic capabilities of the investigated plasma, taking into account its reabsorption in the plasma optical density within 0.1 to 1.3 range.
3. Conclusion
The prototype of the diagnostic system based on the CCD digital video camera and the plasma self-sheathing device allows increasing the accuracy of the spectral radiance and the optical density measurements of a pulsed plasma, minimizing the size of the experimental setup, as well as speeding up and simplifying the data recording and processing.

References
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