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Study of emission spectra in a high-pressure cesium lamp with a pulse-periodic discharge

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The emission spectra of a high-pressure cesium lamp in a pulse-periodic discharge were recorded. It has been shown that with an increase in the discharge power, dips appeared in the spectrum caused by absorption by cesium dimer molecules. These molecules are located in the cold near-wall layer, in which most of the atoms are concentrated at the end of the pulse. Measurement of absorption in diffuse bands with wavelengths of 707, 713 and 719 nm made it possible to estimate the concentration of cesium atoms in the discharge using the known reduced absorption coefficients.

Keywords: emission spectrum, absorption band, cesium dimer molecule, atomic concentration.

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Introduction

Cesium lamps have a high color rendering index and fairly high light output. They also emit in the ultraviolet spectral range (280−350 nm), which makes them well-suited for use in high latitudes. In addition to providing indoor lighting, they will compensate for the deficiency of ultraviolet (UV) radiation, which has an adverse effect on health [1]. To study and optimize the design and operating modes of such lamps, one needs to examine their key parameters, which include cesium vapor pressure p_{Cs} (concentration n_{Cs} of cesium atoms) in the standard operating mode, electron concentration n_e, and electron temperature T_e. Plasma parameters n_e and T_e may be determined using the recombination continuum [2,3].

Pressure p_{Cs} of saturated cesium vapor in experimental devices with cesium filling is normally set by temperature T_c of a special branch with excess liquid cesium (cold point temperature). Cold point temperature T_c is usually 20−30 K lower than the temperature of the device. A discharge in a cesium lamp is maintained in a cylindrical sapphire burner enclosed in a protective cylindrical quartz envelope. In the laboratory model of a lamp, this envelope was connected to the evacuation unit, which made it relatively easy to lead out the thermocouple wires. In operating modes, the envelope was evacuated. Preliminary experiments have demonstrated that the cold point was located at one end of the burner to which a thermocouple measuring the temperature and, consequently, equilibrium pressure p_{Cs} was connected. The design of an evacuated experimental cesium lamp is close to the one used in practice, making the discussed simple method for p_{Cs} determination inapplicable.

It is obvious that the temperature of the burner and, consequently, pressure p_{Cs} increase with an increase in electrical power supplied to the lamp. In the course of experimental examination of various operating modes of a cesium lamp, the power supplied to it varies by a factor of 10 or more. Preliminary experiments and estimates reveal that the cesium pressure changes in these modes by a factor of approximately 100. This makes it clear that independent Cs vapor pressure diagnostics (even with a low accuracy) is needed, if just to get a bearing of the operating conditions. It is evident that if major and labor-intensive modifications to the lamp design are not introduced, only optical diagnostics may help solve this problem. Notably, such measurements need to be carried out for a working lamp emitting intense pulsed radiation, which makes passive diagnostics with an external illuminating source extremely difficult. At the same time, the lamp's own emission may provide useful data on concentration n_{Cs} of cesium atoms. The aim of the present study is to develop optical methods for p_{Cs} (n_{Cs}) diagnostics with the use of characteristic features of the discharge in cesium vapor.

1. Experimental procedure

As was noted above, a cesium lamp consists of a cylindrical single-crystal sapphire burner enclosed in a protective cylindrical quartz envelope. The current leads of electrodes are positioned at the opposite sides of the envelope. The internal diameter of the burner is 5 mm, and the interelectrode distance is 22 mm. In the course of operation, pulses of linearly increasing current of variable polarity are supplied to the electrodes from a special generator. The amplitude of these pulses varies up to 150 A, their duration is 15−50 μs, and the repetition rate is 12−1500 Hz. Prior to sealing, Cs was introduced into the burner, and xenon (Xe) was fed at a pressure of 20 Torr. Xenon is needed to ignite the cold lamp.

The radiation spectrum was recorded using an MDR-23 monochromator; the image of the lamp was focused by a quartz lens onto the entrance slit of the monochromator. A FEU-79 photomultiplier served as the radiation detector. The gated integration method provided an opportunity to record spectra at different moments within a current pulse and after it in decaying plasma with a time resolution of 1 μs. The system for data acquisition and processing also allowed us to record the time dependences of the lamp current and voltage and the lamp emission at a given wavelength.

It turned out to be virtually impossible to use the total absorption method [4] to determine the concentration of cesium atoms in a working cesium lamp, since the brightness of the lamp itself is much higher than the brightness of the continuous-spectrum source (a ribbon lamp with a maximum calibrated brightness temperature of 2431 K at a lamp current of 7 A). Fairly large monochromator slit widths need to set to record the ribbon lamp signal with acceptable accuracy even in the intervals between pulses when the cesium lamp's own radiation is suppressed greatly. With such slits, high-intensity radiation during pulses induces rapid degradation of the photomultiplier.

2. Model

Certain features of the emission spectrum of the lamp may help determine the concentration of atoms. Specifically, dips caused by the absorption by Cs_2 molecules [3] were detected in these spectra. The absorption by Cs_2 and dimers of other alkali metals has been discovered long ago and studied in sufficient detail [5–7]. Such studies were carried out with the use of vessels filled with cesium vapor. A vessel (either made entirely of sapphire or with sapphire windows) was illuminated by radiation from an external source with a continuous spectrum. The cesium pressure was set by the temperature of the vessel. The modes with equilibrium steam and superheated steam (when all the cesium in the vessel was evaporated at a certain critical temperature T_c, and the concentration of atoms in the vessel did not change with a further increase in T) were examined. The temperature dependence of absorption was recorded in these modes.

The case of a cesium lamp differs from this simple scenario of measurement of the absorption spectrum. After ignition, this lamp starts to heat up and gradually (within a few minutes) reaches a steady thermal regime. Since an excess amount of cesium is introduced into the lamp, the cesium pressure also increases monotonically with increasing burner temperature. In the steady thermal regime, the overall amount of cesium vapor in the burner remains unchanged, although the radial distribution of cesium undergoes significant changes within a period. The plasma temperature on the burner axis increases to $(5-10)\cdot 10^3$ K (in certain modes, to $15\cdot 10^3$ K) over the course of a current pulse. The distribution of temperature along the burner radius is fairly flat, although it does decrease rapidly to the level of temperature of the inner burner wall, which does not exceed 1500–2000 K, within a fairly narrow near-wall region. This leads to a strong reduction in concentration of the heavy component (atoms and ions) in the axial region and, conversely, to a sharp increase in this concentration in the narrow near-wall layer. At the same time, the electron concentration decreases profoundly toward the wall, suppressing the emission of recombination continuum from this layer. Thus, continuum radiation from the hot central region of a working cesium lamp illuminates the cold near-wall layer of atoms.

Our experiments on determining the temperature in a cesium lamp [3] revealed that the plasma temperature on the burner axis drops rapidly (within 30–50 μs) to 2000–3000 K after a current pulse, and the radial distribution of concentration of the heavy component is leveled out, although the total number of cesium atoms present within the volume does not change.

3. Measurement results

Figure 1 shows the spectra of the lamp recorded at the end of a current pulse in modes with current amplitude $I_m = 90$, pulse duration $\tau = 50\,\mu$s, and average electric discharge P increasing due to an increase in pulse repetition rate from 400 to 584 Hz. These spectra were corrected for the sensitivity of the detection system. The entrance and exit slits of the monochromator are identical for all spectra (recalculation was made where necessary). It can be seen from Fig. 1 that the integral emission of the lamp intensifies with an increase in P and the burner temperature (the pressure also increases), while the general shape of the

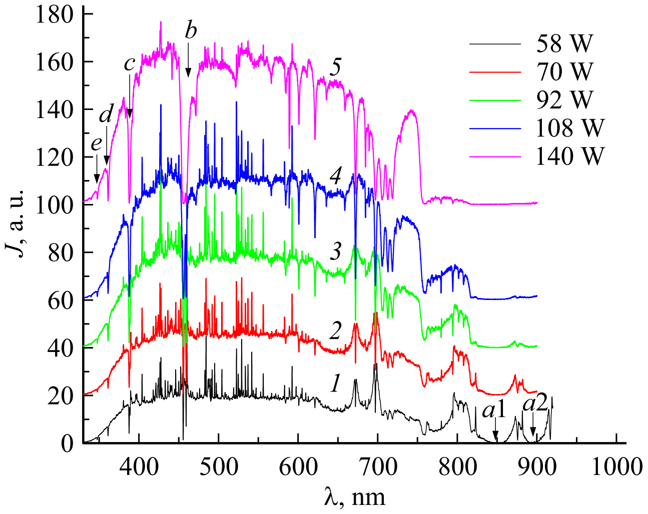

Figure 1. Spectra of a discharge with a maximum current of 90 A and different average power P values, W: *1* — 58, *2* — 70, *3* — 92, *4* — 108, *5* — 140; λ is the wavelength. Arrows $a1$ and $a2$, b, c, d, and e point at the first, second, third, fourth, and fifth resonance doublets of CsI (transitions $6s-np$). Spectra *2–5* are shifted upward by 20, 40, 60, and 100 units, respectively.

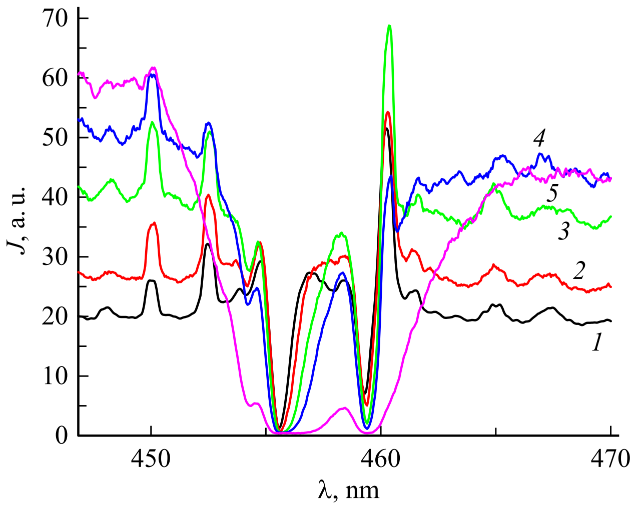

Figure 2. Spectra of a discharge with a maximum current of 90 A in the region of the second resonance doublet for the modes shown in Fig. 1.

continuous spectrum remains practically unchanged. Fairly significant differences between the presented spectra may also be noted. These variations are most notable in the case of emission lines. As power *P* and pressure increase, most lines of both Cs and Xe grow weaker. All doublets of the principal CsI $6s-np$ ($n = 6-12$) series are visible as dips in the continuous spectrum. In the first three doublets, 100% of radiation is absorbed; with increasing power *P*, the absorption bands broaden, and the doublet components merge gradually. Figure 2 illustrates this by presenting a section of the spectrum with the second resonance doublet. A detailed examination of all spectra within the entire wavelength range reveals that, against the background of continuum radiation, dips at the wavelengths of CsI transitions $6p-9s$, $6p-9d$, $6p-8d$, and $6p-7d$ emerge and deepen. Impurity Na, K, and Rb atoms also induce dips at the wavelengths of the first resonance doublets. The spectra of a pulse-periodic discharge in a cesium lamp operated in similar modes were calculated in [8]; however, the process of formation of molecules was neglected in [8], and molecular bands were thus missing in the calculated spectra.

In addition to atomic lines (in emission and absorption), very wide (tens of nanometers) absorption bands, which are associated with Cs_2 molecules, are observed in the experimental spectra. These bands may be examined in more detail in Fig. 3, which shows the spectra for 58 and 140 W. The molecular absorption bands for $P = 140$ W are denoted in this figure as $A-X$ (within the 800–1160 nm range), $B-X$ (750–800 nm), and $E-X$ (440–525 nm) [9,10]. Note that strong absorption within the 800–900 nm range is attributable also to the first resonance doublet of CsI (852.115, and 894.348 nm). The indicated molecular absorption bands are associated with transitions from the ground singlet state of the Cs_2 molecule ($X^1\Sigma_g^+$) with a dissociation energy of 0.46 eV [11]. Owing to their low dissociation energy, Cs_2 molecules dissociate even in the relatively cold near-wall layer with a temperature of 1000–2000 K; their concentration decreases with distance from the wall, and they are virtually lacking in the rest of the lamp volume with a temperature up to 10^4 K.

Three diffuse absorption bands (designated „d.b.“ in Fig. 3) associated with transitions from the ground triplet state of the Cs_2 molecule ($a^3\Sigma_u^+$), which is very weakly bound, are found in the 705–720 nm interval. Figure 4 shows a section of the spectrum with these bands (the wavelengths of absorption maxima are 707, 713, and 719 nm). The coefficient of absorption in the molecular bands of dimers is proportional to the density of molecules

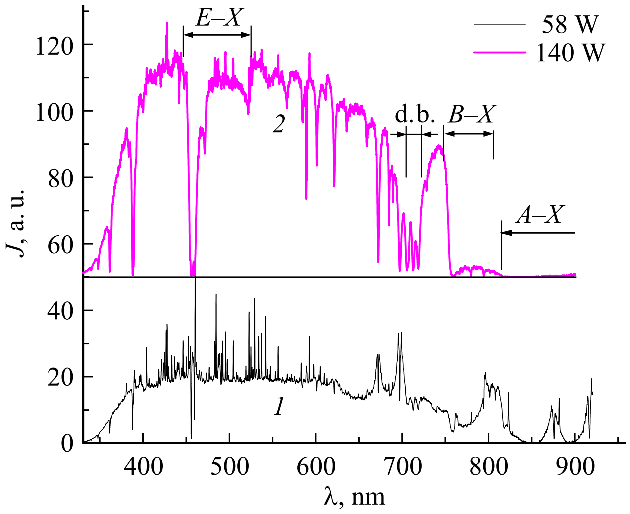

Figure 3. Spectra of a discharge with a maximum current of 90 A and average power *P*, W: *1* — 58, *2* — 140; λ is the wavelength. $E-X$, $B-X$, and $A-X$ — absorption bands of the Cs_2 molecule; „d.b.“ — diffuse bands of the Cs_2 molecule.

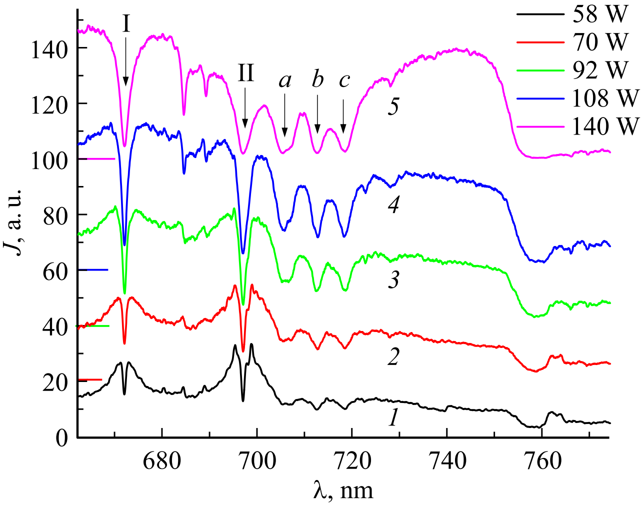

Figure 4. Diffuse absorption bands of the Cs_2 molecule ($a-c$) for the modes shown in Fig. 1. I and II — 672.329 and 697.329 nm lines of the diffuse CsI series (transition $6p-7d$). Spectra *2–5* are shifted upward by 20, 40, 60, and 100 units, respectively.

in the lower state: $k \sim n^2 \exp[-\Delta V_l(R)/k_\mathrm{B}T]$, where n is the concentration of atoms, $\Delta V_l(R)$ is the binding energy of the lower state of the molecule, and k_B is the Boltzmann constant. In the case of weakly bound states ($\Delta V_l(R) \ll k_\mathrm{B}T$), the absorption coefficient is virtually independent of T; therefore, the molecular absorption bands stemming from shallow lower states are most suitable for determining the density of atoms [5], especially when the temperature depends on coordinate. The absorption in these bands was used in [12] to determine the density of cesium atoms.

Molecular absorption coefficient $k = k_R n_\mathrm{Cs}^2$, where k_R is the reduced absorption coefficient and n_Cs is the concentration of cesium atoms. The values of k_R within the 700–725 nm range were measured in [5] by recording the absorption spectra of superheated cesium vapor; it was also demonstrated in this study that the reduced absorption coefficient does not depend on T within the examined range of 600–1000 K. The values of k_R at the maxima of the corresponding bands are as follows (in units of 10^{-36} cm^5):

$$k_R(707) = (0.85 \pm 0.1),\ \ k_R(713) = (1.35 \pm 0.1),$$

$$k_R(719) = (1.2 \pm 0.1).$$

The values of k may be determined from the attenuation of continuum radiation in the cold near-wall layer: $J = J_0 \exp(-kl)$, where l is the absorbing layer length, J_0 is the initial continuum intensity at the layer entrance, and J is the continuum intensity on leaving the layer. The value of J_0 is determined by extrapolating a section of the lamp emission spectrum located near the absorption band. Concentration n_l of cesium atoms in the layer is then written as

$$n_l^2 l = \ln(J_0/J)/k_R.$$

Here, n_l^2 is the root-mean-square value of the concentration of cesium atoms in the layer. The error of this method is specified by the errors of determination of J_0 and J. It increases sharply in the opposite cases of weak ($J_0 \approx J$) and strong ($J \ll J_0$) absorption in the layer. For a $l = 0.1$ cm layer, this yields the following estimates of the minimum and maximum measurable concentrations n_Cs: $3 \cdot 10^{17}$ and $6 \cdot 10^{18}$ cm^{-3}.

Figure 5 presents a section of the spectrum with diffuse bands at $P = 92$ W, which serves as an example for determining J_0 and J and calculating $n_l^2 l$. It can be seen from Figs. 4 and 5 that the error of determination of J_0 by extrapolation may reach 20–30% in different modes. The absorption measurements were performed at the end of a current pulse when the temperature difference between the axis and the wall is at its maximum (5–10 times), allowing one to assume that most of the atoms are localized in this layer with a concentration of n_l.

The values of $n_l^2 l$ calculated from absorption in the diffuse 719 nm band (Fig. 5) in the modes shown in Fig. 1 are listed in the table. The n$_l$ values for two layer thicknesses $l = 0.1$ and 0.05 cm. are also indicated.

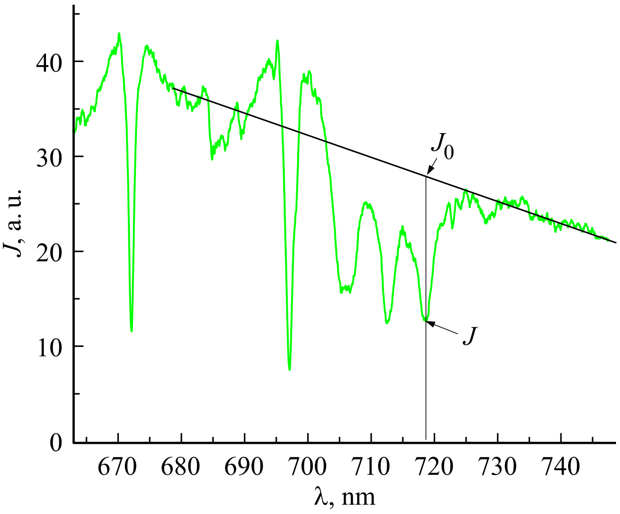

Figure 5. Diffuse absorption bands of the Cs$_2$ molecule for the mode with average power $P = 92$ W.

Values of $n_l^2 l$ as functions of the discharge power and n_l at two different layer thicknesses

Power, W	$n_l^2 l$, 10^{36} cm^{-5}	n_l, 10^{18} cm^{-3} $l = 0.1$ cm	n_l, 10^{18} cm^{-3} $l = 0.05$ cm	n_Cs, 10^{18} cm^{-3}
58	0.27	1.6	2.3	0.9
70	0.35	1.9	2.6	1.1
92	0.52	2.3	3.24	1.3
108	0.75 ± 0.05	2.75	4.0	1.4
140	2.9 ± 0.1	5.4	7.6	2.7

Average concentration n_Cs of atoms in the burner (last column in the table) may be determined under the assumption that all layer atoms are distributed uniformly over the entire cross section of the burner: $n_\mathrm{Cs} = [1 - (r_1/r_0)^2]n_l$, where r_0 is the burner radius and r_1 is the layer boundary radius. The value of n_Cs depends weakly on the hypothetical layer width and corresponds to a (virtually constant along the radius) concentration in the burner at the end of plasma decay when the temperature of the heavy component equalizes in the radial direction and approaches wall temperature T_wall. It is evident that cesium atoms located in the near-axial hot zone of the burner are neglected in the proposed method. Their number may be estimated from the n_l value measured in the cold layer and known temperatures on the axis (T_0) and on the wall of the burner. The number of atoms in the central region of the burner depends on T_0, and the end value may increase by a factor no greater than two at large T_0.

Taking into account the error of determination of J_0 and J and the uncertainty of layer width l, one may state that the absolute values of average concentration n_Cs of atoms in the burner are determined with an accuracy up to 1.5−2. Relative n_{Cs} variations with a change in power are determined with an accuracy of 10−20%.

Conclusion

The emission spectra of a high-pressure cesium lamp with a pulse-periodic discharge were measured and analyzed, and a method for determining concentration n_{Cs} of cesium atoms was proposed. The method is based on measuring the absorption of continuum radiation of the lamp in the diffuse bands at 707, 713, and 719 nm of Cs_2 cesium dimer molecules located in the cold near-wall layer of the burner. The error of this method and the range of n_{Cs} concentrations within which it remains applicable were indicated. Concentration n_{Cs} was determined in a number of modes.

Conflict of interest

The authors declare that they have no conflict of interest.

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