OPTICAL RADIATION CHARACTERISTICS OF LASER-INDUCED AIR PLASMA AND JAMMING CCD IMAGING DETECTOR **

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We studied the characteristics of laser-induced air plasma optical radiation and jamming the imaging CCD detector. Optical emission spectra of the air plasma ranged from 400 to 700 nm are composed of individual spectral lines superposing on continuous radiation, while the continuum radiation is mainly due to bremsstrahlung and recombination radiation. The jamming threshold of the CCD imaging detector jammed by optical radiation of the laser-induced air plasma is 3.98×10^{10} W/cm^2. With increasing laser intensity, the plasma expansion volume and spectral intensity will increase, the image quality of the CCD detector will deteriorate, and the jamming area on the CCD detector will become larger. The experimental results indicate that the jamming effect of laser-induced plasma radiation on CCD detectors can overcome the shortcomings of a single-wavelength laser use, which is important for improving the optoelectronic jamming effect.

Keywords: *laser-induced air plasma, optical radiation, CCD imaging detector, jamming effect.*

ХАРАКТЕРИСТИКИ ИЗЛУЧЕНИЯ ЛАЗЕРНО-ИНДУЦИРОВАННОЙ ВОЗДУШНОЙ ПЛАЗМЫ И ПОМЕХИ ПЗС-ДЕТЕКТОРА

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Изучены характеристики оптического излучения лазерно-индуцированной воздушной плазмы и создание помех в работе видеодетекторов на ПЗС-структурах. Оптические эмиссионные спектры плазмы воздуха в диапазоне 400—700 нм состоят из суперпозиции отдельных спектральных линий и континуума. Континуум состоит в основном из тормозного и рекомбинационного излучений. Порог подавления изображения ПЗС-видеодетектора под действием оптического излучения лазерной воздушной плазмы $3.98 \cdot 10^{10}$ Вт/см^2. С увеличением интенсивности излучения лазера объем лазерно-индуцированной плазмы и спектральная интенсивность возрастают, качество изображения ПЗС-видеодетектора ухудшается и площадь помех на видеоизображении ПЗС-детектора расширяется. Результаты эксперимента показывают, что подавляющее действие излучения лазерно-индуцированной плазмы на ПЗС-видеодетекторы выше, чем в случае монохромного лазерного излучения, что важно для повышения эффективности создания оптоэлектронных помех.

Ключевые слова: *лазерно-индуцированная воздушная плазма, оптическое излучение, ПЗС-видеодетектор, создание помех.*

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Introduction. The CCD (charge coupled device) detector based on the mature MOS (metal oxide semiconductor) process was developed shortly after its invention by Bell Labs [1]. With the further development of semiconductor devices and large-scale integrated circuits, the CCD has acquired a number of advantages, that is, small size, high resolution, high sensitivity, high reliability, and low image distortion [2], which can be widely used in military and scientific research fields, such as remote sensing, telemetry, weapon guidance, satellite reconnaissance, and image tracking [3, 4].

Recently, many research groups have paid more attention to one or two mixed laser wavelengths in terms of CCD detector jamming [5–10]. Wide-spectrum, high-repetition pulses, or fiber lasers [11–13] are mostly used as jamming sources. The response of CCD detectors to different laser wavelengths is different. However, in some applications there is a narrow band-pass filter in front of the CCD chip, which can be applied to protect the CCD imaging. Compared to other jamming sources, laser-induced plasma radiation has a broader spectrum, and its intensity depends on the laser wavelength, laser intensity, ambient gas pressure, target characteristics, etc. To overcome the limitation of a single wavelength laser and increase the jamming efficiency of a laser jammed CCD, laser-induced plasma radiation can be used as the jamming source. Studying the jamming effect of laser plasma radiation on CCD detectors has an important application potentiality on the improvement of laser jamming capability. In the existing studies, nearly no relevant research on plasma radiation jamming of CCD detectors has been observed. In this paper, the jamming effect of optical plasma radiation on the CCD detector is studied experimentally. The spectral characteristics of laser-induced air plasma radiation are analyzed. Meanwhile, the jamming images of plasma optical radiation on the CCD detector under different laser power density are given. Lastly, the jamming mechanism of laser-induced plasma optical radiation on a visible light area CCD array is discussed.

Experimental. The experimental setup to study optical emission of the laser-induced air plasma jamming an imaging CCD detector is shown in Fig. 1. A Nd:YAG laser (wavelength 1064 nm, pulse width 8 ns, and frequency rate 10 Hz) with the laser beam diameter of 10 mm was adopted to generate the air plasma optical radiation. The laser beam was focused on a plane-convex quartz lens (L1) with a focal length of 100 mm to break down and generate air plasma, where the laser energy was adjusted by an energy attenuation system consisted of a half-wave plate and a Glan prism system. Optical radiation of the laser-induced air plasma was monitored by using a beam splitter, while the air plasma optical radiation was acquired by a collection lens (L2) with a focal length of 75 mm and then coupled into a spectrometer (Spectra Pro 500i, PI). The spectrograph was equipped with an intensified charge coupled device (ICCD); the spectral resolution was 0.1 nm at 150 cm^{-1} at 500 nm blaze wavelength, and the spectral range was 350 nm for one acquired measurement. A digital delay generator (DG645, Stanford) was adopted to trigger the laser pulses and control gate delays of the ICCD.

The laser plasma optical radiation jammed a CCD detector (SONY ICX059CL) with an imaging system. The photosensitive element of the imaging CCD detector absorbed the photon energy of laser-induced air plasma radiation and increased the gray value to 256, which induced the imaging saturation in the CCD chip. The CCD detector parameters used in this study are follows: total number of pixels 752(H)×582(V), sensitive area 5.59 mm(H)×4.68 mm(V), substrate material – Si. A filter with high transmittance in the 400–700 nm wavelength and high reflectance at 1064 nm was put in front of the CCD detector. The distance of the reference image and the plasma was 20 cm; the distance between the CCD detector and the plasma was 6 cm. Because of the CCD high sensitivity to light radiation, the plasma radiation jamming experiment was conducted in a dark environment to reduce the influence of surrounding light radiation on the CCD. The whole experiment was examined under 1 atm pressure, room temperature of 25^{o}C, and relative humidity of 25%.

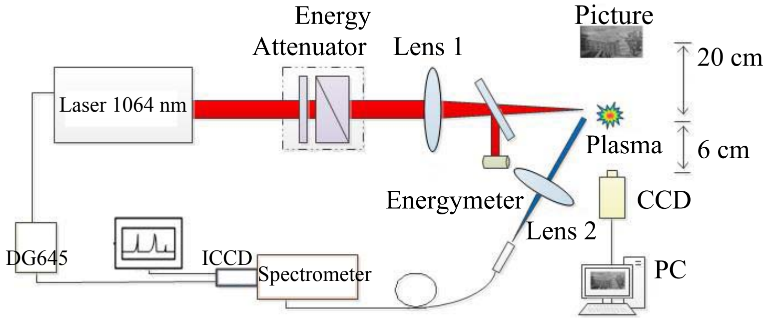

Fig. 1. Experimental setup of CCD jamming by plasma radiation.

Results and discussion. As shown in Fig. 2, the optical emission spectra of the air plasma ranged from 400 to 700 nm depending on the laser radiation intensity. The air plasma spectra are composed of a superposition of individual spectral lines and continuum emission. The continuum spectrum intensity of the 370–530 nm band is higher than that of the 530–700 nm band. Bremsstrahlung and recombination radiation of electron-ions is considered as the main mechanism of continuum emission. The high-intensity short-wavelength continuum emission (370–530 nm band) from air plasma is mainly produced by the bremsstrahlung radiation, while the low-intensity long-wavelength continuum emission (530–700 nm band) is mainly produced by the recombination radiation. The whole integral intensity of the spectra from 400 to 700 nm as a function of the laser intensity is shown in Fig. 3.

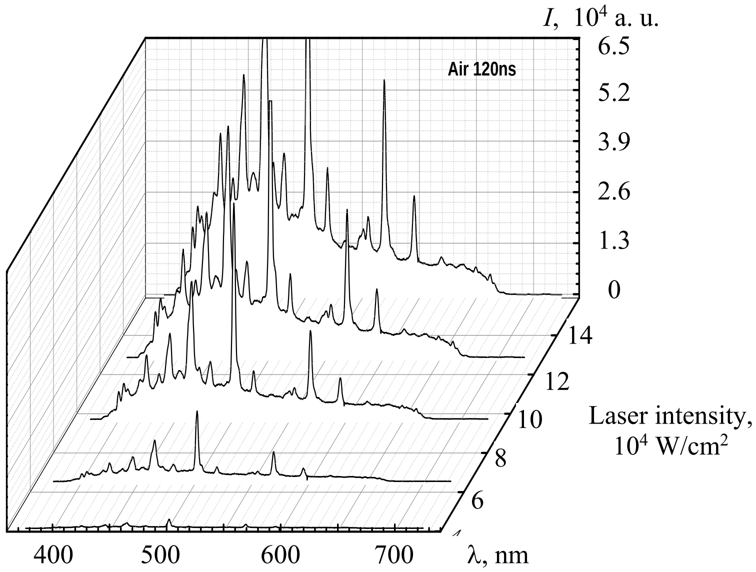

Fig. 2. Spectra of air plasma radiation (400–700 nm) vs laser intensity.

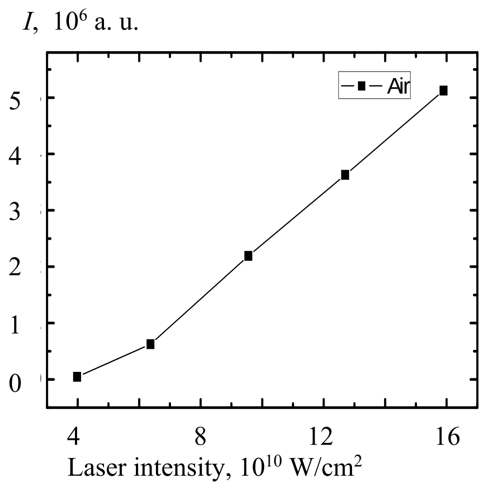

Fig. 3. Integral spectral intensity (400–700 nm) vs laser intensity

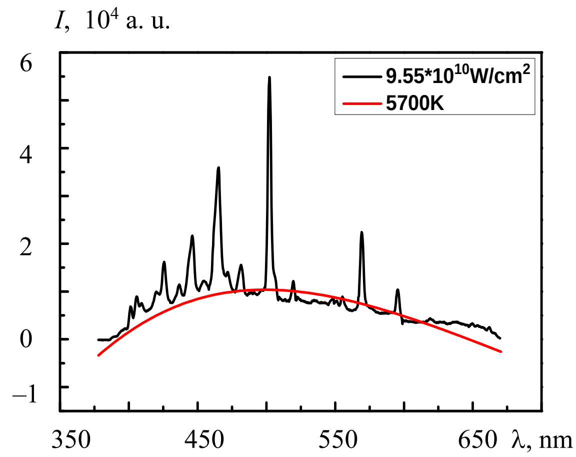

Fig. 4. Estimation of plasma temperature from blackbody radiation

Both the spectral intensity of the continuum and individual lines increase with increasing laser intensity, increasing the whole integrated spectral intensity. With the laser intensity increase, the air plasma can absorb more laser energy by the process of inverse bremsstrahlung [14], which increases the plasma temperature, prolongs the decay time of the plasma, and thus increases the continuum spectral intensity. Also, the excited atomic particles increase with the laser intensity by the process of collision ionization, which leads to the spectral intensity growth of individual lines. During the imaging CCD detector working, the displayed image on CCD will be jammed as the plasma optical radiation on the CCD chip becomes stronger.

Plasma temperature and electron density are two important characteristic parameters of plasma. By calculating temperature and electron density of air plasma, the jamming action of plasma optical radiation on the CCD detector can be studied more deeply. Regarding the jamming by plasma radiation of the CCD detector, the main consideration is the effect of the continuous spectrum of plasma radiation on the CCD. For the sake of easy calculation, we assumed the plasma to be a blackbody in a state of thermal equilibrium. The plasma temperatures were estimated using Planck's law. When the laser intensity is 9.55×10^{10} W/cm^2, the plasma temperature is estimated at around 5700 K (Fig. 4). The plasma temperatures varied with the laser radiation intensity as shown in Fig. 5. The plasma temperature increases with the laser radiation intensity.

The electron density in the plasma is related to the broadening of the spectral lines. In the case of assuming local thermal equilibrium, the spectral line broadening is mainly due to Stark broadening, so the electron density N_e is given by the following equation:

$$\Delta\lambda_{1/2} = 2\omega N_e/10^{16}, \tag{1}$$

where w is the Stark broadening parameter. The electron density is estimated using the Stark-broadened profile of the O II 464.9 nm line from Eq. (1). The electron density at different laser radiation intensities is shown in Fig. 6.

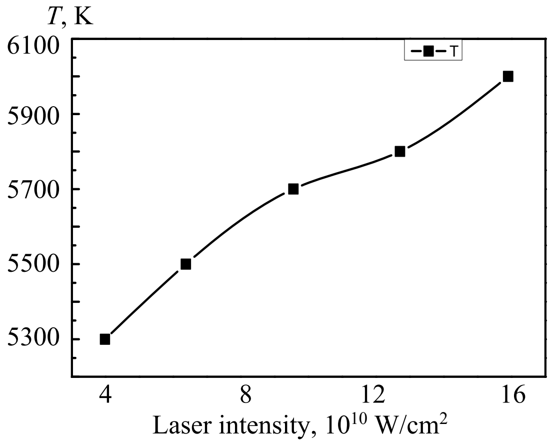

Fig. 5. Air plasma temperature vs laser intensity.

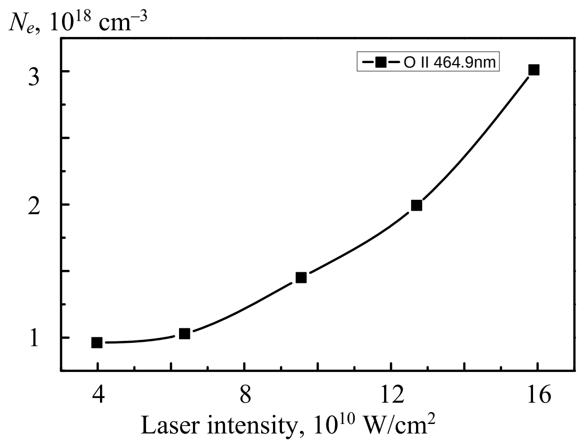

Fig. 6. Air plasma electron density vs laser intensity.

The CCD images obtained at jamming by the air plasma optical radiation produced with different laser intensity are shown in Fig. 7. In our experiment, the jamming threshold of the CCD detector induced by the air plasma optical radiation is 3.98×10^{10} W/cm^2, which defines the pixel gray value in the CCD detector to a maximum value of 255, which is larger than the air plasma generation threshold of 3.66×10^{10} W/cm^2. As the laser intensity increases and exceeds the jamming threshold of the CCD detector, the CCD image quality decreases, and some image information is lost, which means that the CCD imaging detector is jammed by the air plasma optical radiation.

The jamming area on the CCD detector can be written as follows:

$$S = \frac{A\times5.59\times4.68}{752\times582}(\text{mm}^2), \tag{2}$$

where A is the total number of pixels in the jamming area, 752×582 is the total number of pixels in the CCD chip, and 5.59×4.68 mm^2 is the photosensitive area in the CCD chip. The jamming area on the CCD detector can be calculated by the jammed photos obtained varying with laser intensity as shown in Fig. 8. The expansion volume and spectral intensity of the laser-induced air plasma all increase with growth in laser intensity; thus, the jamming effect of the CCD detector induced by the air plasma optical radiation can be enhanced, which leads to a continuous increment of the jamming area on the CCD imaging detector.

Fig. 7. Jamming the CCD imaging detector by air plasma optical radiation vs laser intensity: no pasma (a), 3.98×10^{10} (b), 9.55×10^{10} (c), and 15.9×10^{10} W/cm^2 (d).

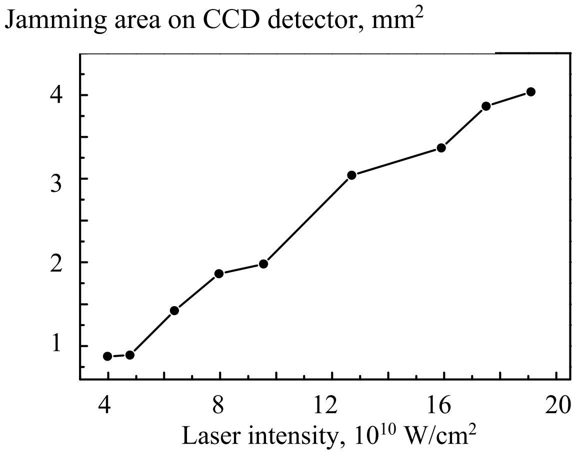

Fig. 8. The CCD detector jamming area vs laser intensity.

When the air plasma optical radiation is acquired on the imaging CCD detector, the expansion volume and the whole integral spectral intensity of the plasma increased with laser intensity increase. This leads to an increment in the number of photoelectrons and in a photosensitive area on the CCD detector. Thus, the gray value of the imaging can be increased. As the number of signal charges exceeding the capacity of the electron potential well increases, the signal charges flow out to an adjacent potential, and the gray value of imaging can be 255 for the radiated photosensitive element, which means that the image quality of the CCD detector decreased, inducing the jamming effect for the CCD imaging detector. As the laser intensity increases, the image quality of the CCD detector deteriorates and the jamming area S on the detector becomes larger.

Conclusions. This article proposes jamming a CCD imaging detector by optical radiation of the laser-induced air plasma. The optical emission spectra of the air plasma ranging from 400 to 700 nm are composed of individual spectral lines superposing on continuous emission. The continuum emission mainly comes from bremsstrahlung and recombination radiation; moreover, the high-intensity short-wavelength continuum emission (370–530 nm band) is mainly produced by the bremsstrahlung radiation, while the low-intensity long-wavelength continuum emission (530–700 nm band) is mainly produced by the recombination radiation. The jamming threshold of the imaging CCD detector jammed by the laser-induced air plasma optical radiation is 3.98×10^{10} W/cm^2. When the laser intensity increases, the expansion volume and spectral intensity of the laser-induced air plasma get larger. When the signal charge number converted by the photoelectric conversion exceeds the capacity of the electron potential well in the CCD chip, the signal charge will flow out to the adjacent potential well. This leads to the jamming effect for the imaging CCD detector; the image quality of the CCD detector; will deteriorate, and the jamming area on the CCD detector will become larger. The CCD detector jamming by the laser induced plasma radiation can overcome the disadvantages of a single-wavelength laser use. Therefore, this study is important to improve the optoelectronic jamming effect.

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