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RESEARCH ARTICLE

Origin of peculiar inerratic diffraction patterns recorded by charge-coupled device cameras

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Abstract A peculiar and regular diffraction pattern is recorded while using either a color or a monochrome charge-coupled device (CCD) camera to capture the image of the micro air plasma produced by femtosecond laser pulses. The diffraction pattern strongly disturbs the observation of the air plasma, so the origin and eliminating method of these diffraction patterns must be investigated. It is found that the Fourier transform of the periodic surface structure of either the mask mosaic of the color CCD or the pixel array of the monochrome CCD is responsible for the formation of the observed pattern. The residual surface reflection from the protection window of a CCD camera plays the essential role in forming the interesting two-dimensional diffraction spots on the same CCD sensor. Both experimental data and theoretical analyses confirm our understanding of this phenomenon. Therefore removing the protection window of the CCD camera can eliminate these diffraction patterns.

Keywords charge-coupled device (CCD), scattering, ghost reflection

1 Introduction

Besides its vast application in consumer products like digital cameras, an important imaging device, the charge-coupled device (CCD) has been extensively employed in laboratories and industries [1]. To obtain overall high opto-electronic conversion efficiency, anti-reflection (AR) coating is normally applied on the CCD sensor surface for effectively reducing the surface reflection [2,3]. However, $1\%-10\%$ of reflection of the incident light at the CCD surface is still typical [4]. For CCD cameras used in various scientific and industrial applications, their sensors are often protected by a thin cover glass with or without AR coating.

In our recent studies of the scattering properties of the femtosecond laser induced micro air plasma, a peculiar inerratic diffraction pattern was frequently observed in the images recorded by an old color CCD camera [5]. While we replaced the color camera with a monochrome one, the inerratic diffraction pattern was still observed although the details of the pattern were different. In this paper, we report our observation and understanding of such diffraction spot pattern taken with different CCD cameras. It is revealed that the cover glass of the CCD camera actually plays an essential role in forming this pattern. The array of the monochrome CCD pixels or the mosaic mask in the color CCD reflects the incident coherent light back to the cover glass, and the reflection at cover glass surface causes part of the reflected light to bounce back to the CCD sensor surface again. In such a process, when certain alignment condition that will be addressed in the following is met, a Fourier transform of the CCD pixel or the mask mosaic that functions as a two-dimensional grating or a spatial modulator can be realized and caught by the same CCD detector. Both theoretical simulation and experimental studies are presented to support our understanding of this interesting Fourier transform process.

2 Experiments

The experimental setup is shown in Fig. 1(a). The micro air plasma is first generated through focusing a beam of 1 kHz, 800 nm femtosecond laser with a 5 × objective (NA = 0.1). (In the following, we shall consider the scattering center of this micro plasma as a perfect point source noted as S). Another 800 nm femtosecond laser beam, namely, the probe light is focused by a 10 × objective (NA = 0.25) and

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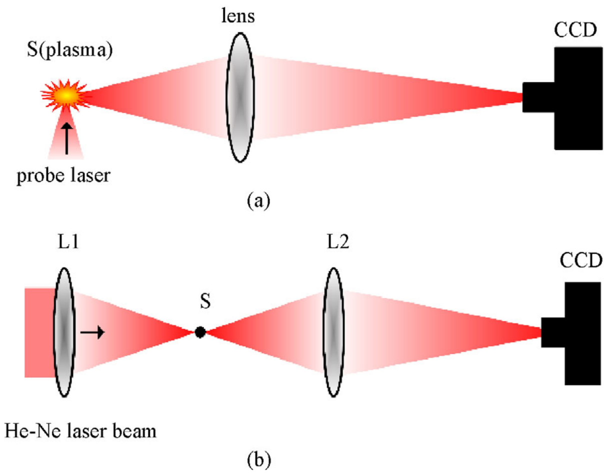


Fig. 1 Schematic of experimental setups for imaging the air plasma generated by a femtosecond laser beam propagating in a direction normal to the picture plane (a) and for using a He-Ne laser beam to produce a coherent point source to mimic the origin of the peculiar diffraction pattern (b). In (a), the focused probe laser beam is scattered by the micro plasma and the scattered light is collected by the imaging lens and detected by the CCD camera

propagates through the air plasma. The two laser beams are normal to each other and both propagating in the same horizontal plane. The scattered light from the micro plasma is collected by a 4 × objective (NA = 0.1) in the direction normal to the horizontal plane and detected by a CCD camera. The distance between the point source and CCD camera is ~35 cm. Therefore, it can be calculated that the maximal incident angle of light entering the CCD camera is ~0.01 rad. Two CCD cameras are respectively used in our experiments. One is a color CCD with mask mosaic structure on the CCD sensor and the other is a monochrome one. They both have a protection cover glass.

When the sensor surface of CCD is situated right at the image plane of the air plasma, the image of the plasma, i.e., the point source S, is clearly captured by the CCD camera. When the CCD camera is slightly translated from this imaging position toward the lens, however, a rather peculiar inerratic diffraction pattern may emerge, which is as shown in Fig. 2. In Fig. 2(a), the picture is taken with an old scientific-grade color CCD camera, and the large bright central spot corresponds to the blurred (also saturated) image of point source S. By examining such a picture, a basic cell like that outlined by the yellow rectangular in Fig. 2(a) can be easily recognized. As illustrated by the drawing shown in the up-right corner, within the basic cell three sub-groups of spots may be identified. Namely, the brightest spots marked by the four pentagrams are at each corner of the cell; five vertical spots marked by small circles in the middle, being of next level brightness; and the rest, also the least bright two spots marked by the solid dots sandwiched between the four brightest ones at the corners.

Figure 2(b) shows the diffraction spots of the same object captured by the monochrome CCD camera we purchased (Lu135M, Lumenera Inc.). It can be seen that in this case the diffraction pattern is much simpler than that obtained with the color CCD camera, and the spatial frequencies of the two are also rather different. It should be noted that if no probe beam, one cannot observe the diffraction spots.

By repeating the experimental observations like those given in Fig. 2, it is confirmed that the distances among the recorded regular spots are actually independent of the imaging condition, namely, it neither depends on the image magnification ratio nor the focal length of the imaging lens. Moreover, changes of the femtosecond laser power and pulse duration also do not alter these observed diffraction patterns. This thus leads us to speculate that the peculiar diffraction pattern is unlikely due to any possible spatial structures within the micro plasma that diffracts the probe light.

To validate this hypothesis, a separate experiment is performed that focuses a 632.8 nm He-Ne laser to a tiny

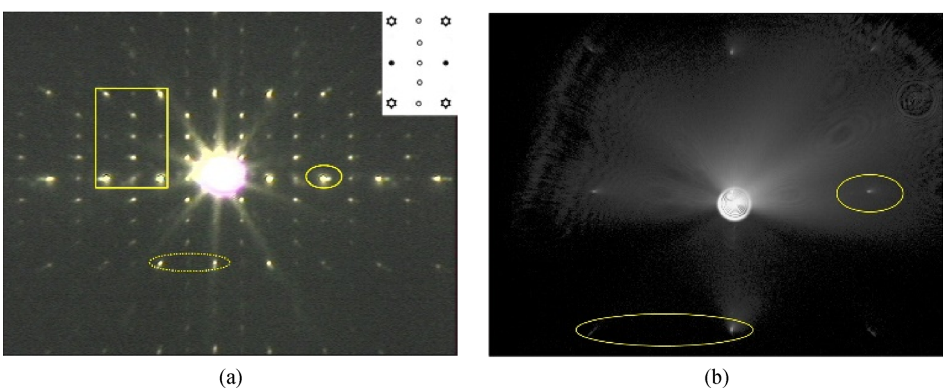


Fig. 2 Inerratic diffraction patterns captured by a color (a) and a monochrome (b) CCD cameras with 800 nm femtosecond laser pulse illumination. The frame sizes of Figs. 2(a) and 2(b) are 4.8 mm × 3.6 mm and 6.5 mm × 4.8 mm, respectively. In Fig. 2(a), a basic cell of the diffraction pattern is outlined by the rectangle on the left of the central bright spot, which is further described by the pattern given at the up-right corner. In the latter, markers to represent different levels of brightness are used for the purpose of further analysis

spot to mimic the point light source and then the same color/monochrome CCD camera is used to capture its image. The specific experimental setup is as shown in Fig. 1(b) and the results are given in Fig. 3. The spot patterns of Figs. 3(a) and 3(b) are somewhat similar to those in Figs. 2 (a) and 2(b) except the differences in spatial frequencies. For example, the spatial frequency of the brightest spots circled by the dotted ellipses in Figs. 2(a) and 3(a) are 16.7/cm and 21.0/cm respectively, and those circled in Figs. 2 (b) and 3(b) are 4.9/cm and 6.2/cm respectively. These values clearly illustrate that the spatial frequencies of the observed spot patterns are inversely proportional to the wavelength of the incident light.

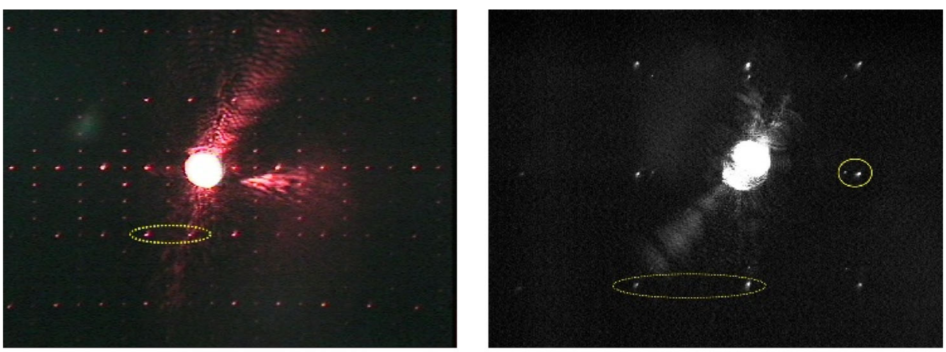
It is also interesting to notice that in Fig. 3(b) near each scattered spot there appears a secondary spot, such as the one surrounded by the solid ellipse on the right. These less bright secondary spots form a new set of spot matrix with a spatial frequency slightly higher than that of the brighter ones, and their relative positions with respect to the central spot are also constant, namely, not being affected by the imaging condition. (Note that such secondary spots, are actually also identifiable in Figs. 2(a) and 2(b), although it is apparently more obscure)[1)]. In further searching for the real origin of the inerratic diffraction pattern, we then remove the cover glass of the CCD sensor. And the matrix of spots is no longer observed. Therefore, it becomes obvious that these regular diffraction spots are related to the presence of the cover glass. It is also found that these regular diffraction patterns can be observed clearly only when the image on CCD camera is approximately a point. For large images, the diffraction spots may overlap with each other which cannot be resolved.

3 Discussion

In the following, by numerical simulation we confirm that the periodic structure of the CCD pixels is equivalent to a planar two-dimensional reflective grating, and the observed diffraction spots are actually the Fourier transform of such a grating. It is the reflection of the CCD cover glass that helps to fulfill such Fourier transform by projecting the Fourier transform image right back on the same CCD sensor.

Figure 4(a) shows the light path when the incident light enters a CCD camera with a cover glass. Normally, the CCD imaging sensor should be placed at the imaging plane to catch the image S′ of the point light source S. During experiments, however, the CCD camera needs to be translated in finding a sharper image, and this may lead to the fact that the imaging sensor being placed before the actual imaging plane by a distance specified with L_2. At this forward-shifted position the light partially reflected by the CCD sensor surface and then reflected by the cover glass will go back to the CCD sensor the second time. In this case, if the amount of the forward translation L_2 is exactly twice of the separation between the CCD sensor surface and its cover glass, L_1, the sensor surface will be the de facto imaging plane for the surface reflected light. In this case, the diffraction spot pattern will be clearly recorded. It should be noted that in the optical path arrangement like the one shown in Fig. 4(a), the pixel array of the CCD acts as a planar reflection grating and the reflected incident light that carries the pixels' modulation will be captured by the same pixel array as a result of the surface reflection from the cover glass.

It is well-known that Fourier transform of an optical object may be obtained through a single lens imaging system [6]. In particular, a 2D object and its Fourier transform can be both on the same side or each on different side of the imaging lens. But the former case is more pertinent to the case shown in Fig. 4. Under the illumination of a quasi-monochromatic spherical wave, the multi-reflection process sketched in Fig. 4(a) can be



(a) (b)

Fig. 3 Inerratic diffraction patterns captured respectively by a color (a) and monochrome (b) CCD camera with a 632.8 nm He-Ne laser (see Fig. 1(b)). The sizes of Figs. 3(a) and 3(b) are 4.8 mm × 3.6 mm and 6.5 mm × 4.8 mm, respectively

1) Such secondary spots do not appear to be evidently present as is in Fig. 3(a), which could be caused by both too low intensity and not enough resolution

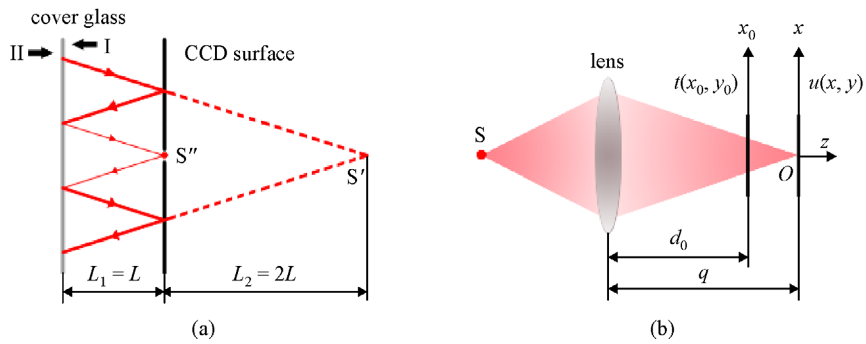


Fig. 4 (a) Optical path of the light rays inside a CCD camera with a cover glass whose two surfaces are marked respectively by letters I and II. L_1 is the distance between surface of the cover glass and the sensor surface; S′ corresponds to the image of the point source S; S″ is the image of the same point source S formed by consecutive reflection from the sensor surface and the cover glass. (b) Equivalent single lens optical imaging model of the experimental setup associated with (a) and that in Fig. 1

unfolded and made equivalent to the optical layout shown in Fig. 4(b), for which the complex amplitude at the output plane (CCD sensor surface) is given by [7]

$$u(x,y) = c' \exp\left[\mathrm{j}k\frac{x^2+y^2}{2(q-d_0)}\right]$$

$$\int_{-\infty}^{+\infty}\int t(x_0,y_0)\exp\left(-\mathrm{j}k\frac{x_0x+y_0y}{q-d_0}\right)\mathrm{d}x_0\mathrm{d}y_0, \quad (1)$$

where x, y are the output (image) plane coordinates, c' is a constant, $k = 2\pi/\lambda$ (λ is the wavelength of the incident light), x_0, y_0 are the input (object) plane coordinates, $t(x_0, y_0)$ is the transmittance function of the object, q and d_0 are the respective image and object distances from the lens. Apparently, the relation $(q - d_0) = 2L_1$ should hold.

Equation (1) tells us that $u(x, y)$ equals to the Fourier transformation of $t(x_0,y_0)$ multiplied by a parabolic phase. In our case, $t(x_0, y_0)$ corresponds to the pixel array of the CCD sensor. From Eq. (1), the spatial frequencies f_x, f_y are determined by

$$f_x = x/[\lambda(q-d_0)], \quad (2)$$

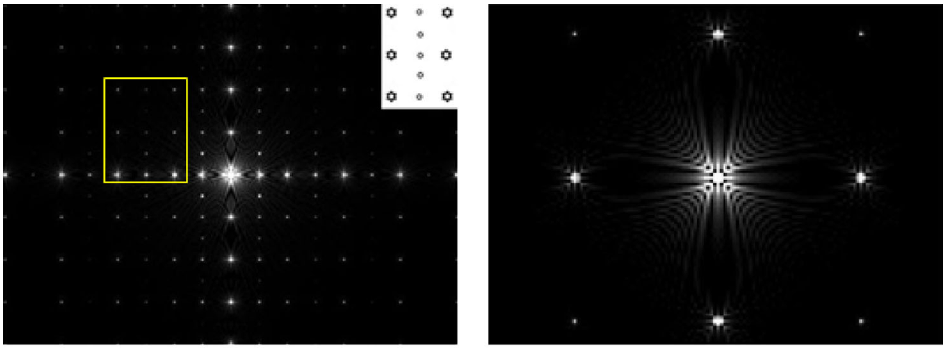
$$f_y = y/[\lambda(q-d_0)], \quad (3)$$

which are inversely proportional to the product of λ and $(q - d_0)$. The wavelength dependence of the spatial frequency derived from the experimental data given in Figs. 2 and 3 can thus be well explained by Eqs. (2) and (3). It is clear that if any three of the four parameters in either expression given above are known [$(q - d_0)$ is considered as one parameter], the fourth one can be then readily derived. For example, in the experimental results of Fig. 2(b), the values of f_x (or f_y), λ, and x (or y) are 0.215 μm^{-1}, 800 nm, and 1.979 mm respectively, and therefore the distance between the cover glass and the front surface of CCD sensor will be 5.76 mm according to Eq. (2), which is in good agreement with the actual value (the measured result is 5.70 mm). As shown in Fig. 3(b) a secondary set of spots exists besides the primary diffraction spot pattern. Existence of these two sets of spot pattern is attributed to the respective reflection at the two surfaces of the cover glass. The exact difference of the spatial frequencies between the two sets of spot pattern should then contain the information of both thickness and refractive index of the cover glass.

Based on Eq. (1), numerical simulation of the Fourier transform of the specific CCD sensor surface associated with the optical setup in Fig. 4(b) has been performed and the typical results are shown in Fig. 5. In particular, Fig. 5 (b) corresponds to the measured picture in Fig. 2(b), where a grating period of 4.65 μm is assumed which is just the pixel size of the monochrome CCD sensor. Such a simulation result agrees with the experimental observation. To simulate the experimental result given in Fig. 2(a), we first make some trials to determine the mask type on the color CCD we used. Altogether, three types of color mask are simulated for Bayer filter, three color filter, and complementary filter respectively. Figure 5(a) is the simulation result of the Fourier transformation of the complementary filter, which shows a reasonably good match with the experimentally recorded diffraction pattern except the discrepancy in spot brightness.

4 Conclusions

In conclusion, it is demonstrated that in a simple optical imaging system composed of a single lens and a CCD camera with a cover glass the Fourier transform image of the CCD sensor pixels or the mask mosaic filter array for a color CCD can be captured by the same CCD sensor itself. The residual reflection at the CCD sensor surface and from the CCD cover glass plays the essential role in the formation of this Fourier transform. Such results are useful



(a) (b)

Fig. 5 (a) and (b) are the simulated results based on Eq. (1) corresponding to the measured diffraction patterns given in Figs. 2(a) and 2 (b) respectively. Frame size: (a) 7.7 mm × 5.8 mm, (b) 6.5 mm × 4.8 mm

in reminding optical engineers and/or pertinent users that a CCD camera with a parallel protection glass window used in coherent imagining applications may lead to a faulty or artificial inerratic diffraction spot pattern in the captured images. Thus, care must be taken to obviate mistaking these spot patterns as the real images of an object under study. Finally, it is possible that this interesting observation might be also explored as a simple and practical approach to examining CCD cameras without opening up the camera package.

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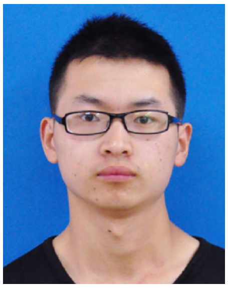

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