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Outfield experiment of semiconductor laser jamming on color CCD camera

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ABSTRACT

Outfield laser jamming experiment of color charge coupled device (CCD) irradiated by semiconductor laser was performed. The impact of incident power density I_0 and the focus length f on laser jamming results was obtained. Laser jamming model of color CCD camera is set up, and theoretical proving and analysis on experimental results are completed. Laser jamming effects on color CCD camera irradiated by semiconductor laser is obvious, CCD surface appears obvious optical saturation and crosstalk phenomena, and optical saturation areas gradually enlarge with the increase of power density to target and the focus length *f*. Simulation results are basically coincident with experimental results, and it proves laser jamming model is correct. We argue that optical saturation phenomenon should be caused by laser diffraction effect, and the impact of the focus length *f* should be mainly due to laser energy truncated by the aperture. The conclusions have a reference value for color CCD in aerospace.

1. Introduction

Charge coupled device (CCD) is widely used in detection, recognition, identification, tracking and inspection, either for civilian or military purposes. However, they can be easily dazzled by high power laser. To avoid the jamming effects, its phenomena and mechanisms must be known and understood. Recently, researches on laser jamming photoelectric device especially CCD device are reported [1–4]. The researches almost cover all from the visible to the infrared band, and a lot of experiments on laser jamming CCD device are performed [5–8]. The literature [5] has studied the laser jamming effect of 1064 nm CW laser to linear CCD camera. The literature [6] and [7] studied laser jamming effect of planar array CCD induced by pulsed laser, and the impact of laser energy、pulse width and repetition frequency on CCD device is measured. Besides, optical saturation threshold and temperature rise on CCD device induced by combined fiber laser have been analyzed in literature [8].

However, all these studies above aim at black and white CCD device and are performed in the lab. There has been rarely reported till now on out-field laser jamming analysis of color CCD camera. Because color CCD camera gets images clearer, it makes color CCD camera gain the advantage on target imaging, target identification, surveying and mapping. At present, color CCD camera is chosen as the sensor in a large of photoelectric equipments, such as surveying and mapping camera in aerospace. Therefore, the research on out-field laser jamming experiment of color CCD device has a practical significance.

In this paper, we not only set up laser jamming model of color CCD imaging system, but also performed out-field laser jamming experiment of color CCD camera induced by semiconductor laser at 1.3km. Laser jamming mechanism is analyzed and the impact of incident power density I_0 and focus length f of color CCD imaging system on laser jamming effect is obtained.

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2. Laser jamming model of color CCD

The main mechanism of laser jamming CCD device is photoelectric effect. The basic element of CCD device is metal-oxide-semiconductor (MOS) capacitor, and its capacitance is defined as [9]:

$$C_i = \frac{\varepsilon_0 \varepsilon s}{d} \tag{1}$$

Where ε_0, ε, s, d is respectively dielectric constant, relative dielectric constant、cross section area of deep depletion layer and thickness of insulating layer. The memory limit Q_l of signal charge is a constant in MOS capacitor, and the value is associated with MOS capacitance C_i, grid voltage V_G and initial surface voltage V_{so} of CCD.

$$Q_l = C_i(V_G + V_{so}) \tag{2}$$

$$V_{so} = \frac{Q_{fc}}{C_i} - V_{ms} \tag{3}$$

Where Q_{fc} is the charge quantity of surface oxidation layer, V_{ms} is contact potential difference of metal and semiconductor.

As laser-induced charge generation time of CCD induced by high energy laser is far less than its integral time, a lot of signal charges are collected in the MOS capacitor. For the intrinsic CCD device, laser-induced charge Q_s accumulating in the integral time can be expressed as:

$$Q_s = (1 - R)es\eta I_0 t_0/h\nu \tag{4}$$

Where R is the reflectivity of CCD's surface, e is electronic charge, η is quantum efficiency, I_0 is incident laser power density, t_0 is the CCD integral time, ν is the frequency of incident laser.

Surface voltage V_s would decrease with the increase of Q_s. When V_s equals to initial surface voltage V_{so} of MOS capacitor nearby, laser-induced charge Q_s would diffuse to the nearby MOS capacitor. Crosstalk phenomenon takes place, and normal imaging signal could not be achieved. With laser incident power to further enlarge, when Q_s reaches its limit Q_l, the depletion layer of MOS capacitor is totally filled. Signal charge Q in the MOS capacitor would not increase anymore with the increase of laser incident power, and optical saturation phenomenon takes place. The typical parameters [8] of visible imaging CCD are shown as Table 1.

Diffusing process of signal charge Q is shown in Fig. 1. Assuming that MOS capacitor corresponding with focusing beam is in the center of CCD device. Signal charges Q in four MOS capacitors which are adjacent to the core MOS capacitor would gradually increase owing to diffusing effect. Once signal charge Q from laser-induced and diffusing effect in the four MOS capacitors is more than its limit Q_l, diffusing phenomenon will keep on until signal charge Q is less than its limit Q_l in some MOS capacitor. Diffusing charge quantity Q_{ci} in some MOS capacitor could be defined as:

$$Q_{c_i} = \mu(Q_{s_i} + Q_{c_{i-1}} - Q_l) \tag{5}$$

Where Q_{si} and Q_{li} are laser-induced charge quantity in a MOS capacitor and its limit, μ is charge transfer efficiency. It is noteworthy that voltage barrier at the horizontal direction is much higher than voltage barrier at the vertical direction. Therefore, diffusing charge quantity at the horizontal direction is less than diffusing charge quantity at the vertical direction. In this model, the diffusing ratio between the horizontal direction and the vertical direction is defined as 1:19.

Bayer filter is used for spectral splitting in single CCD color camera, which is placed on the CCD chip, and consists of a series of micro lens. Those micro lens are mainly classified as red spectral microloan、green spectral microloan and blue spectral microloan, and their arrangement is shown in Fig. 2. In this case, the impact of Bayer filter is taken into account in the model.

In this paper, numerical simulation method is used to solve the above model. Assuming that optical system of color CCD is equivalent to a lens. According to basic theory of laser propagation, beam through a lens will produce an additional phase, and its complex amplitude can be defined as [10]:

$$U_T(x, y) = U(x, y)T(x, y) \tag{6}$$

Where T(x,y) is complex amplitude transfer function. For thin spherical lens, T(x,y) can be defined as:

Table 1
Main parameters of CCD device.

Parameter	Value
s	2×10^{-10}m^2
V_G	10V
d	10^{-7}m
ε	3.9
V_{ms}	−0.85V
Q_{fc}	3.2×10^{-13}C
η	0.6
R	0.35

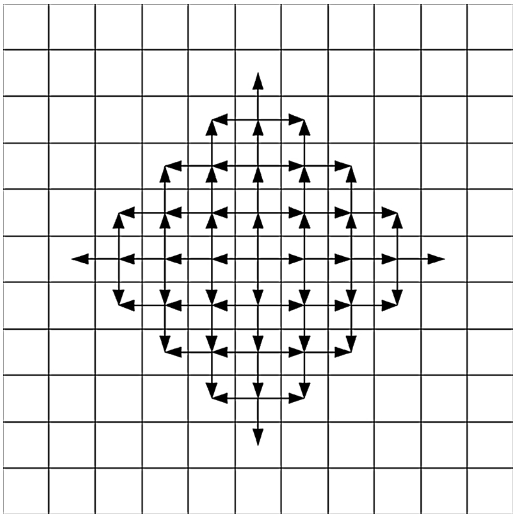


Fig. 1. Diffusing process of signal charge Q (arrow represents charge overflow direction, and a check represents a pixel).

T_G	T_R	T_G	T_R	T_G	T_R
T_B	T_G	T_B	T_G	T_B	T_G
T_G	T_R	T_G	T_R	T_G	T_R
T_B	T_G	T_B	T_G	T_B	T_G
T_G	T_R	T_G	T_R	T_G	T_R
T_B	T_G	T_B	T_G	T_B	T_G

Fig. 2. Bayer filter arrangement.

$$T(x, y) = p(x, y)\exp\left(-ik\frac{x^2 + y^2}{2f}\right) \tag{7}$$

Where f is focus length of optical system, p(x,y) is pupil. Laser propagation schematic diagram in CCD optical system is shown in Fig. 3. Semiconductor laser irradiates on CCD surface through a lens and aperture. The aperture diameter is usually less than the lens diameter. Therefore, p(x,y) should mainly depend on aperture's shape and size. In the model, the shape of the aperture is assumed as circular, and the size of the aperture is calculated by F number and focus length f of color CCD imaging system.

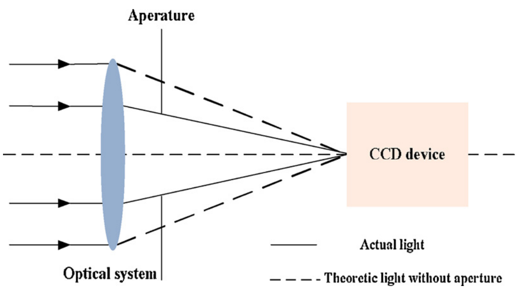


Fig. 3. Schematic diagram of laser propagation in optical system.

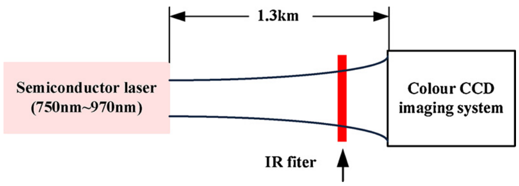


Fig. 4. Schematic diagram of experimental set-up.

3. Out-field laser jamming experiment of color CCD imaging system

3.1. Experimental set-up

Schematic diagram of experimental set-up is shown in Fig. 4. Color CCD imaging system is irradiated by multi-wavelength semiconductor laser. In the experiment, multi-wavelength semiconductor laser is placed in the indoor, and color CCD imaging system is placed in the outdoor 1.3 km.

The experiment is divided three parts: one is the jamming experiment of 750 nm semiconductor laser to color CCD imaging system, another is the jamming experiment of multi-wavelength semiconductor laser to color CCD imaging system, and the last is the jamming experiment of multi-wavelength semiconductor laser with IR filter to color CCD imaging system.

Output power and wavelength of semiconductor laser in the experiment mainly include 750 nm(160 W)、780 nm(210 W)、808 nm(210 W)、880 nm(210 W) and 970 nm(210 W), and 750 nm semiconductor laser could separate. The other main parameters of semiconductor laser are shown in Table 2.

Color CCD imaging system mainly includes optical system and color CCD camera. F number of optical system is 5, focus length f is 120 mm, diameter D is 40 mm, and transmittance T is 0.5. Color CCD camera is ICX409AK camera of Sony company, pixel number and size of which is 752 × 582 and 6.5 μm × 6.25 μm respectively. Response curve of ICX409AK camera is shown in Fig. 5.

IR filter is a product of Edmund optical company, the transmittance T of more than 800 nm is nearly 1%. Transmittance curve of IR filter is shown in Fig. 6.

3.2. Experimental results and analysis

Power density to CCD surface is estimated by formula (8).

$$I = \frac{4P_0\tau_a\tau_l}{(l\times\theta)^2\times\pi\times d^2}D_0^2 \tag{8}$$

d is diameter of focusing beam in the formula, the value can be defined as:

$$d = 2.44\lambda F \tag{9}$$

Where P_0 is initial laser power, τ_a is atmospheric transmittance, τ_1 is transmittance of optical system, D_0 is diameter of optical system, l is laser jamming distance, θ is beam divergence angle, λ is wavelength, and F is F number of optical system. In the experiment, atmospheric visibility is 3 km above. Atmospheric transmittance curve of 400 nm–1100 nm laser calculated by Modtran software at 1.3 km is shown in Fig. 7.

Laser jamming effect of multi-wavelength semiconductor laser (750 nm ~ 970 nm) to color CCD imaging system with the focus length f 120 mm is firstly measured in the experiment. The experimental results are shown in Fig. 8 and Table 3.

We could find that laser jamming effect of 750 nm laser with a output power of 160 W to color CCD imaging system is obvious in Fig. 8(b), and optical saturation phenomenon appears in the center of laser jamming image. White bright line should be crosstalk line, its appearance shows color CCD camera has happened laser crosstalk phenomenon. Comparing with Fig. 8(c) and (d), we can also find that laser jamming effect gradually enlarge with the increase of laser output power. When output power of multi-wavelength semiconductor laser(750 nm–970 nm) is up to 1000 W, color CCD camera occurs the whole CCD surface saturation.

In addition, some regular speckles could be found in Fig. 8(b) and (d). We argue that the speckles should be caused by stray light. A small part of laser transmitting to the optical system is deflected by the frame, and its power is very low. Thus, the regular speckles take shape through optical system.

Table 2
Main parameters of semiconductor laser.

Parameters	Value
model	CW, adjustable power
Initial diameter	30mm
Divergence angle	≤5mrad
Power	≤1000 W
Power instability	≤5%

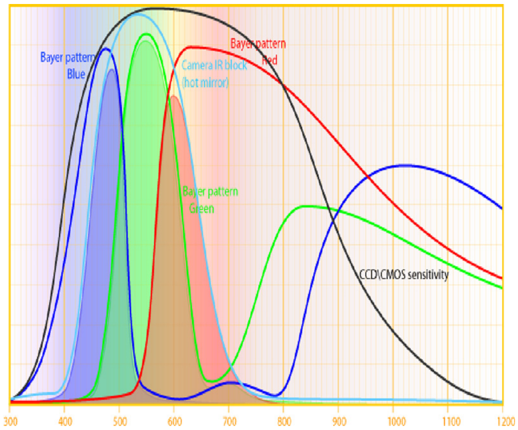


Fig. 5. Response curve of ICX409AK camera.

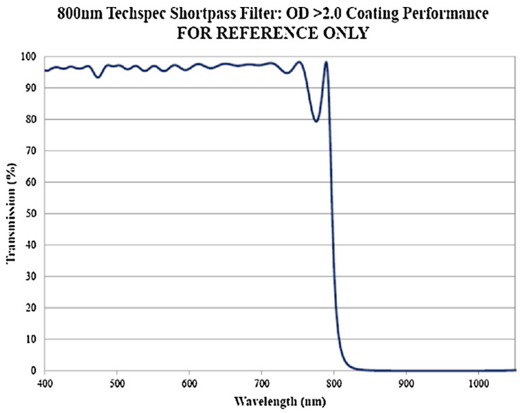


Fig. 6. Transmittance curve of OD2.0 short wave passing filter.

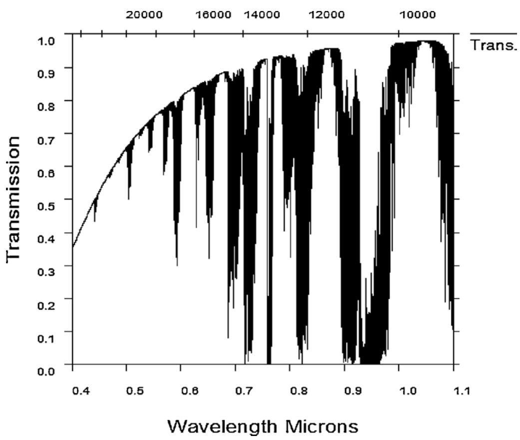


Fig. 7. Atmospheric transmittance of 400 nm–1100 nm laser at 1.3 km.

Laser jamming simulation results of color CCD imaging system calculated by the model are shown in Fig. 9. Optical saturation and crosstalk phenomena are obvious in the simulation images. Optical saturation area of three jamming simulation images is respectively 1.0 mm × 1.0 mm、entire CCD surface saturation and 1.5 mm × 1.5 mm. Simulation results are basically coincident with experimental results, and it proves laser jamming model is correct.

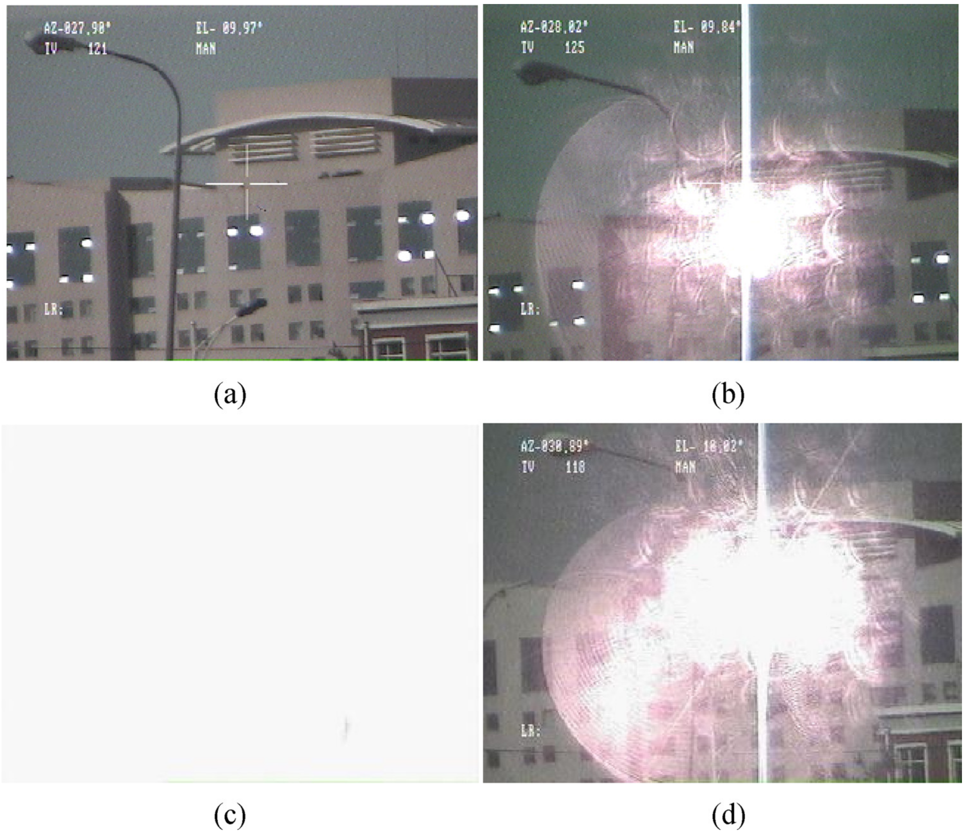


Fig. 8. laser jamming effects of color CCD imaging system (a) background; (b) 750 nm laser ; (c) multi-wavelength laser(750 nm–970 nm) ; (d) multi-wavelength laser(750 nm–970 nm) with IR filter.

Table 3
Laser jamming results of color CCD imaging system.

wavelength	Power	Power density to CCD surface	distance	optical saturation area
750 nm laser	160 W	4.2 kW/cm^2	1.3 km	1.8 mm × 1.2 mm
750 nm–970 nm laser	1000 W	20.7 kW/cm^2	1.3 km	the whole surface saturation
750 nm–970 nm laser with IR filter	370W	9.2 kW/cm^2	1.3 km	2.1 mm × 1.7 mm

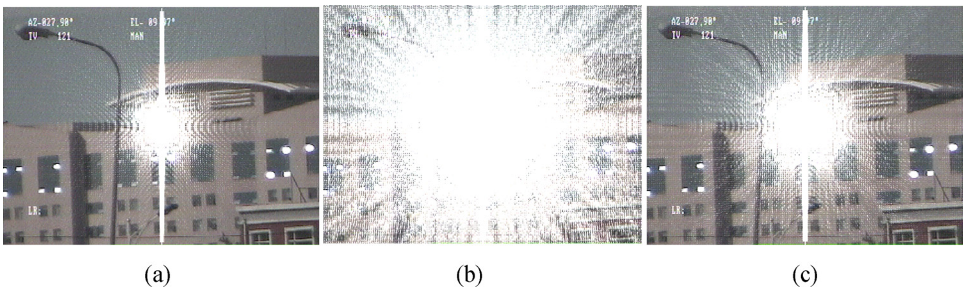


Fig. 9. laser jamming simulation results of color CCD imaging system (a) 750 nm laser ; (b) multi-wavelength laser ; (c) multi-wavelength laser with IR filter.

3.3. Laser jamming mechanism

In order to analyze laser jamming mechanism, laser-induced charge Q_s distribution of CCD induced by 750 nm laser in an integral time is shown in Fig. 10.

We can find that laser-induced charge quantity Q_s mainly focuses on several pixels at laser irradiation center. It means that

$Q_s/10^{-12}C$		Pixel at the horizontal direction						
		158	159	160	161	162	163	164
Pixel at the vertical direction	118	110	8.9	290	23	280	12	78
	119	180	120	1.7×10^3	1.2×10^3	1.7×10^3	98	250
	120	290	81	270	1.1×10^4	340	85	280
	121	480	1.2×10^3	2.2×10^4	8.1×10^4	2.2×10^4	1.2×10^3	480
	122	280	85	340	1.1×10^4	270	81	290
	123	250	98	1.7×10^3	1.2×10^3	1.7×10^3	120	180
	124	78	12	280	23	290	8.9	110

Fig. 10. laser-induced charge Q_s distribution at irradiation center.

diameter focusing on CCD surface is much smaller than optical saturation area. It is also found that laser-induced charge Q_s of all MOS capacitors in the optical saturation area is more than its limit Q_l(4.78×10^{-13}C) in Fig. 10. Therefore, laser-induced charge Q_s in optical saturation region should be generated by laser diffraction effect. Diffraction effect should be the main cause of laser jamming.

Besides, laser-induced charge Q_s focuses on several pixels and is mainly diffuse to the vertical direction. Therefore, crosstalk phenomenon should occur at laser irradiation center. It is coincident with experimental phenomenon.

3.4. Laser jamming analysis of zoom optical system

Zoom optical system is widely used in the practical application, and its laser jamming effect is different from optical system with fixed focus length. Relationship between focus length *f* of optical system and optical saturation area is calculated by laser jamming model. The simulation results are shown in Fig. 11.

It is found that optical saturation area gradually enlarges with the increase of focus length *f* in Fig. 11. When focus length *f* is 17mm, 60 mm and 120 mm, optical saturation area is respectively 0.2 mm × 0.2 mm, 0.55 mm × 0.56 mm and 0.96 mm × 0.95 mm. The corresponding simulation images are shown in Fig. 12.

We argue the main cause of weak laser jamming effect on 750 nm laser to optical system with short focus length is laser energy truncated by the pupil. Fig. 13 gives laser power density distribution with different focus length f to explain the conclusion. It is found that beam diameter to CCD surface is the same, while power density to CCD surface is different. It shows that the impact of the focus length *f* does not depend on beam diameter to CCD surface and mainly depends on power density to CCD surface. Owing to the same F number, the pupil diameter gradually diminishes with the decrease of focus length *f* of optical system. Thus, a large part of laser energy is truncated by the aperture to optical system with short focus length, and it makes laser jamming effect weak.

Laser jamming experiment of zoom optical system is performed and experimental results are shown in Fig. 14.

It is found that optical saturation area and crosstalk line gradually enlarge with the increase of focus length *f* of optical system. Optical saturation area of focus length *f* 17mm, 60 mm and 120 mm is respectively 0.33 mm × 0.29 mm、0.75 mm × 0.66 mm and 1.8 mm × 1.2 mm. It is basically consistent with the conclusion above. While optical saturation area measured in the experiment is a litter more than the results calculated by laser jamming model. The main cause is that the impact of the stay light is ignored in laser jamming model.

4. Conclusion

In summary, laser jamming effect of color CCD camera irradiated by multi-wavelength semiconductor laser(750 nm–970 nm) is measured at 1.3 km in this paper, and theoretical proving and analysis is completed by laser jamming model of color CCD camera. Laser jamming effect of color CCD camera irradiated by semiconductor laser is very obvious, and optical saturation and crosstalk

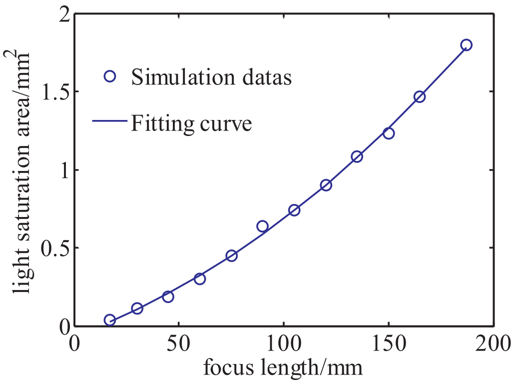
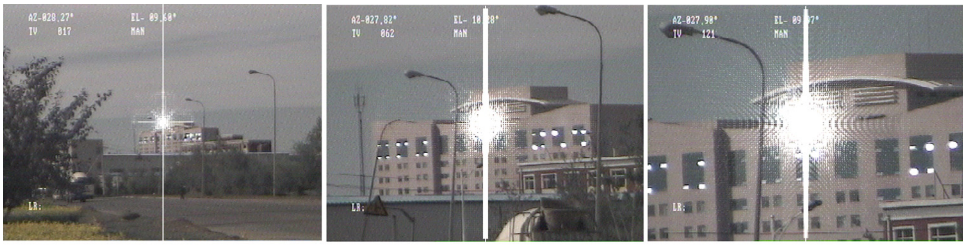
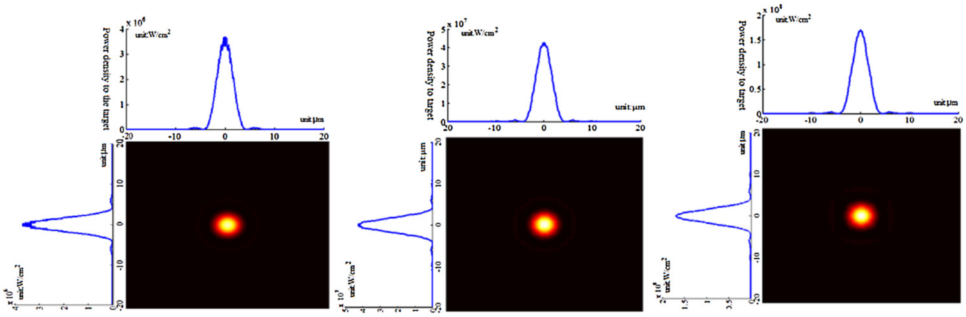


Fig. 11. Relationship curve between focus length f of optical system and optical saturation area.



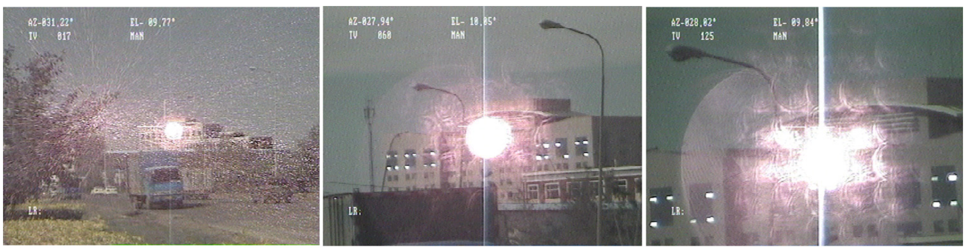
(a) (b) (c)

Fig. 12. Laser jamming simulation images of zoom optical system (a)f = 17 mm; (b)f = 60 mm; (c)f = 120 mm. Laser jamming simulation images of zoom optical system (a) f = 17 mm, (b) f = 60 mm, (c) f = 120 mm.



(a) (b) (c)

Fig. 13. laser jamming simulation images of zoom optical system (a) f = 17 mm, (b) f = 60 mm, (c) f = 120 mm.



(a) (b) (c)

Fig. 14. laser jamming effects of zoom optical system (a) f = 17 mm, (b) f = 60 mm, (c) f = 120 mm.

phenomena are found on the CCD surface. Laser-induced charge Qs of all MOS capacitors in the optical saturation area are almost more than its limit Q_l(4.78 × 10–13 C), and optical saturation phenomenon should be caused by laser diffraction effect. Laser energy truncated by the pupil gradually increase with the decrease of focus length f of optical system, and laser jamming effect would gradually weaken.

In addition, it is worth noting that optical saturation area measured in the experiment is a litter more than the results calculated by laser jamming model. The main cause is that the impact of the stay light is ignored in laser jamming model. The stay light analysis will be carried out in the following study.

References

[1] Y. Xu, X.Q. Sun, L. Shao, Simulation of laser jamming and its influence on CCD imaging performance, Proc. SPIE 7850 (2010) 78501W-1-78501W-8.
[2] H.M.A. Schleijpen, J.C. Heuvel, A. Mieremet, et al., Laser jamming offocal plane array cameras, Proc. SPIE 6543 (2007) 65431B-1–65431B-10.
[3] T. Jiang, Z. Zhang, X.G. Cheng, Study on 'vertical bright line' image of CCD camera irradiated by laser, Proc. of SPIE 7656 (2010) 76561A-1-76561A-5.
[4] J. Xu, S.H. Zhao, R. Hou, et al., Laser-jamming technique research based on combined fiber laser, Opt. Laser Technol. 41 (4) (2009) 686–694.
[5] Z.H. Zhang, X.A. Cheng, T. Jiang, et al., A jamming phenomenon of CW laser on linear CCD camera, Optik 123 (2012) 223–227.
[6] Z.H. Zhang, X.A. Cheng, R. Wang, et al., Jamming effect of repetitive short pulse laser on TDI CCD camera, Opt. Laser. Eng. 49 (2011) 292–296.
[7] A. Durecu, P. Bourdon, O. Vasseur, Laser-jamming effects on TV-cameras: analysis of jamming effects and experimental parameters weight assessment, Proc. SPIE 6738 (2007) 67380L-1-67380L-6.
[8] J. Xu, S.H. Zhao, R. Hou, et al., Laser-jamming analysis of combined fiber lasers to imaging CCD, Opt. Laser. Eng. 47 (2009) 800–806.
[9] C.W. Sun, Laser Irradiation Effects, National Defense Industry Publishing Company, 2002 in Chinese.
[10] J.C. Li, Laser Diffraction and Thermal Effect Calculate, science press, Beijing, 2002, pp. 154–159 in Chinese.