Research on Laser Weapon Soft Damage to IR Seeker

Yanwu Liu
School of Information and Electronics Engineering
Shandong Institute of Business and Technology
Yantai , China 264005
Email: yanwuliu@126.com

***Abstract*—Aiming at ship-borne laser weapon damage to anti-ship missile, laser soft damage to IR seeker was researched. First, link model on laser disturbance to anti-ship missile IR detector was set up. Laser atmospheric transmittance on the sea was deduced. 1.06μm laser atmospheric transmittance on the sea was calculated. The relationship was obtained among atmospheric transmittance and visibility and elevation. Then 10.6μm laser atmospheric transmittance curve was described. The curve is changed by visibility and propagation distance. And then the experiment on laser disturbing CCD imaging system was accomplished. Pixel saturation threshold was measured. CCD saturation power density threshold was also measured. The curve was described. The curve is changed by laser incident energy and CCD saturation area ratio. Saturated area is increasing rapidly with the laser energy increasing; when laser energy is low. Saturated area is increasing slowly with the laser energy increasing; when laser energy is large. Finally, 1.06μm laser was given as an example, the necessary laser energy which can disturb effectively anti-ship missile IR detector was calculated. Some valuable data and conclusions were gained.**

***Index Terms*—laser weapon, laser disturbance, IR detector, atmospheric transmittance**

I. Introduction

At present, the new anti-ship missiles have become increasingly advanced, with sea-skimming flight and end of the motor. They pose a serious threat to ship. While the various ship-based anti-missile system could not fully meet the requirements battle. Thus ship-borne laser weapons came into being. Laser weapons will revolutionize the battlefield because of the unique features of the speed of light. It will be an important new concept weapon.

Mechanism of laser disturbance to photoelectric detector has been studied by many scholars [1][2]. Saturation threshold and damage threshold are obtained by experimental methods [3]. But it is quite rare that necessary laser energy was inferred based on these known data. 1.06μm laser irradiating infrared detector was given as an example. 1.06μm and 10.6μm laser atmospheric propagation property was researched on the sea. The experiment on He-Ne laser disturbing CCD imaging system was accomplished. The necessary laser energy which can damage effectively the IR homing anti-ship missile detector was calculated.

II. Link Model on Laser Disturbance to Anti-ship Missile IR Detector

Laser weapon is divided into two kinds according to destruction effect on anti-ship missile. One kind is the soft destruction. Laser destroys some devices of IR seeker, such as optical system, the electronic primary device, the photo detector and so on. This caused system's function to lose. The other kind is the hard destruction. Laser destroys missile's cowling, the power unit, the warhead and so on. The hard destruction is ruinous, the system will lose the bearing capacity to present the detonation. Usually, laser destruction threshold value of soft destruction is lower than hard destruction[4].

The anti-ship missile is made of shell body, power unit, warhead, guidance system and so on. IR seeker is homing control system of missile. And IR detector is the key device of IR seeker, it is sensitive to the light response. So IR detector is easily attacked by laser weapon. In missile's several major parts, the IR seeker is the key target which laser weapon attacks.

Link model on laser disturbance to anti-ship missile IR detector was set up. Figure 1 is the link model.

The performance of laser weapons is influenced by the

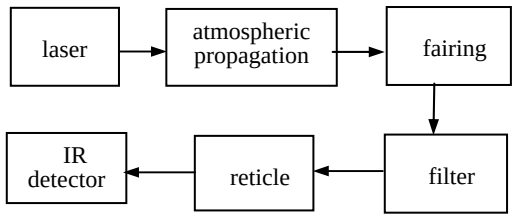

Fig.1. Link model on laser disturbance to anti-ship missile IR detector

weather[5]. Atmospheric conditions have strong influence on laser atmospheric propagation. Research on laser atmospheric propagation is an important research domain of opto-electronic countermeasure. Laser atmospheric propagation has a direct relationship with the transmitting power of the laser. Therefore, it is very

doi:10.4304/jcp.6.6.1238-1245

important to study laser atmospheric transmittance on the sea.

III. LASER ATMOSPHERIC PROPAGATION PROPERTY

A Aerosphere Structure

Aerosphere is classified as five layers by temperature, ingredient and ionization state in vertical direction, troposphere (<10km), stratosphere (10~50km), mesosphere (50~80km), thermosphere (80~500km), exosphere (>500km). Troposphere has most influence upon laser atmospheric propagation. Atmospheric content of troposphere is 80 percent of the entire aerosphere. Weather change mainly appears in troposphere. Table Ⅰ [6] is the ingredient and content of atmosphere on sea surface.

TABLE Ⅰ
THE INGREDIENT AND CONTENT OF ATMOSPHERE ON SEA SURFACE

Ingredient	Molecular weight	Content	
		%	10^{-6}
N_2	28.0134	78.084	
O_2	31.9988	20.948	
Ar	39.948	0.934	
CO_2	44.010		322
Ne	20.183		18.18
He	4.003		5.24
O_3	47.998		0.04
Kr	83.80		1.14
Xe	131.30		0.087
H_2	2.016		0.5
H_2O	18.015		

B Laser Atmospheric Propagation Optical Effect

Laser atmospheric propagation is affected by all kinds of factors. Laser atmospheric propagation comes into being two kinds of effects. One is linearity optical effect, including atmospheric refraction, atmospheric absorption, atmospheric scattering, and atmospheric turbulence. The linearity optics effect is independent of laser intensity. The other is nonlinear optical effect, including Raman scattering, thermal blooming, atmospheric breakdown and so on. The nonlinear optics effect is correlative with laser intensity.

C Linear Optical Effect

1) Atmospheric refraction. Because atmospheric density is not equality, laser propagation path becomes curly. The phenomenon is named atmospheric refraction. Refractivity depends on light wavelength, air temperature, air humidity, altitude and so on.

2) Atmospheric absorption. Atmosphere affects laser propagation, so laser energy will be attenuated. Within the range of linearity optics, laser intensity obeys Beer law with propagation distance z.

$$I(\upsilon, z) = I_0(\upsilon)\exp[-(\alpha + s)z] \tag{1}$$

In the formula (1), $I_0(\upsilon)$ is the laser intensity of $z = 0$ plane; α is absorption coefficient; s is scattering coefficient; sum of α and s is extinction coefficient; υ is frequency. If there are aerosol particles, aerosol extinction coefficient will be considered. Atmospheric molecule absorption depends upon molecule absorption spectrum property.

3) Atmospheric scattering. Because of the asymmetry of atmospheric molecule, aerosol particles and atmospheric turbulence, laser will be scattering. There are molecule scattering and particulate scattering.

4) Atmospheric turbulence. Random changes of atmospheric temperature and pressure result in random change of refractivity with space and time. The phenomenon is named atmospheric turbulence. Atmospheric turbulence results in laser beam excursion, laser beam intensity change, phase change. Research on theory and experiment indicates that adaptive optics techniques are very valid for compensation of laser atmospheric propagation [7][8].

D Nonlinear Optical Effect

For high energy laser propagation in the atmosphere, the nonlinear role between atmosphere and laser will make laser drift, expansion, distortion, or bending. Because the atmosphere absorbs laser energy, leading to light the way of heating, its refractive rate distribution is changed, in turn, the refractive rate changes affect the propagation characteristics of the laser beam[9][10].

1) Thermal blooming. Molecules and ions in the atmosphere will absorb the laser energy when high energy laser is transmitting in the atmosphere. The density of molecules and ions which are heated expansion will decrease. Local refractive rate is reducing. Wave-front distortion of laser beams and beam expansion will appear because of the nonlinear role between atmosphere and laser. The phenomenon is known as thermal blooming.

2) Stimulated Raman scattering. Molecules produce electromagnetic polarization in the incident light irradiation. It gives rise to multi-pole electromagnetic vibration or rotation. The scattering is known as Raman scattering. It involves a lot of energy exchange between scattering photon and the scattering medium. Scattering light frequency is different from incident light. The methods to restraint stimulated rotational Raman scattering are increasing firing a laser beam diameter to reduce the laser power density, using long-wavelength, short pulse and wide-band laser and so on.

3) Atmospheric breakdown. When the laser power density is very high, the gas is ionized to form plasma. The laser energy is most of the plasma “shield”, sound of an explosion wave, accompanied by sparks and whistle sounds. It is known as the atmospheric breakdown. In particular, when the aerosol particles are present in the

atmosphere, the breakdown threshold value will be significantly reduced. Atmospheric breakdown threshold value is usually more than 10^8 W/cm^2. Atmospheric breakdown will not be a serious obstacle for high energy laser propagation in the atmosphere.

IV. LASER ATMOSPHERIC PROPAGATION ON THE ON THE SEA

A. Atmospheric Transmittance on the Sea

Laser energy will be attenuated, when laser propagates in the atmosphere. P_λ is laser power; dx is propagation distance. So formula (2) is tenable.

$$\frac{dP_\lambda}{P_\lambda} = -[\alpha(\lambda) + \gamma(\lambda)]dx = -\mu(\lambda)dx \qquad (2)$$

$\alpha(\lambda)$ is absorption coefficient; $\gamma(\lambda)$ is scattering coefficient; $\mu(\lambda)$ is attenuation coefficient.

Integral of formula (2) is as follows:

$$P_\lambda(x) = P_{\lambda 0} \exp[-\mu(\lambda)x] \qquad (3)$$

$P_{\lambda 0}$ is radiation power of $x = 0$; $P_\lambda(x)$ is radiation power of propagation distance x.

So atmospheric transmittance is as follows:

$$\begin{aligned}\tau(\lambda) &= \frac{P_\lambda(x)}{P_{\lambda 0}} = \exp[-\mu(\lambda)x] \\ &= \exp[-\alpha(\lambda)x] \bullet \exp[-\gamma(\lambda)x] \qquad (4) \\ &= \tau_\alpha(\lambda) \bullet \tau_\gamma(\lambda)\end{aligned}$$

$\tau_\alpha(\lambda)$ is atmospheric absorption transmittance; $\tau_\gamma(\lambda)$ is scattering transmittance.

Large numbers of experiments indicate that atmospheric transmittance nearly correlates with wavelength. The reason is that atmospheric absorption and atmospheric scattering correlate with wavelength. There are some wave bands of high transmittance in atmosphere transmittance spectrum, such as 1~2.7μm, 3~5μm, 8~13μm and so on.

B. 1.06μm Laser Atmospheric Transmittance on the Sea

1.06μm laser atmospheric propagation depends on many factors, such as elevation, temperature, visibility, aerosol style, path length, altitude and so on. Theory and experiments indicate that laser energy attenuation mainly ties to aerosol absorption and aerosol scattering. Absorption and scattering of vapor and CO_2 molecule is 1 percent of total attenuation. Atmospheric aerosol parameter is not easily metrical[11]. So some aerosol models have been summarized according as observation results. They are country aerosol, city aerosol, ocean aerosol and desert aerosol. 1.06μm laser atmospheric transmittance may be calculated according to formula (5).

$$T = \exp\{-\sec\theta \bullet K / V_M [1 - \exp(-0.835H)]\} \qquad (5)$$

The formula (5) is fit for 1.06μm laser propagation from sea surface to certain altitude H or opposition propagation direction. H is altitude; K is constant, K depends on aerosol style, in ocean aerosol, K equals to 4.543km; V_M is visibility; θ is zenith angle. When laser propagates in low elevation, θ is between 85° and 90°. Atmospheric transmittance is respectively calculated, when level propagation distance is 5km and 8km. Table Ⅱ, table Ⅲ and table Ⅳ are the results.

TABLE Ⅱ
1.06UM LASER ATMOSPHERIC TRANSMITTANCE (%) X=5KM

V_M(km) / H (km)	2	5	10	15	23
0.4	0	3.94	19.84	34.02	49.50
0.3	0	3.47	18.62	32.61	48.15
0.2	0	3.03	17.41	31.18	46.76
0.1	0	2.63	16.21	29.72	45.33
0.05	0	2.43	15.60	28.97	44.58
0.03	0	2.37	15.41	28.74	44.35
0.01	0	2.30	15.18	28.45	44.06
0.005	0	2.20	14.84	28.03	43.62

TABLE Ⅲ
1.06UM LASER ATMOSPHERIC TRANSMITTANCE (%) (%) X=8KM

V_M(km) / H (km)	2	5	10	15	23
0.4	0	0.57	7.56	17.87	32.53
0.3	0	0.46	6.81	16.68	31.10
0.2	0	0.37	6.11	15.51	29.66
0.1	0	0.30	5.44	14.36	28.20
0.05	0	0.26	5.11	13.78	27.46
0.03	0	0.25	5.02	13.60	27.23
0.01	0	0.24	4.90	13.39	26.94
0.005	0	0.22	4.72	13.06	26.52

TABLE Ⅳ
1.06UM LASER ATMOSPHERIC TRANSMITTANCE (%) (%) X=10KM

VM(km) / H (km)	2	5	10	15	23
0.4	0	0.16	3.97	11.63	24.59
0.3	0	0.12	3.48	10.67	23.23
0.2	0	0.09	3.04	9.73	21.89
0.1	0	0.07	2.63	8.84	20.55
0.05	0	0.06	2.43	8.40	19.88
0.03	0	0.06	2.37	8.26	19.67
0.01	0	0.05	2.30	8.10	19.41
0.005	0	0.05	2.20	7.85	19.03

C. 10.6μm Laser Atmospheric Transmittance on the Sea

The main attenuation factor is the molecular absorption and aerosol attenuation for 10.6μm laser atmospheric propagation. Atmospheric attenuation of the lower atmospheric transmission is mainly aerosol attenuation, and attenuation of atmospheric molecules can be ignored.

The distribution of aerosol changes exponentially.

$$N(H) = N(0)\exp(-\frac{H}{H_0}) \tag{6}$$

N (H) is indicated H height of the aerosol number density. N (0) is indicated aerosol number density at sea level. H_0 is the aerosol elevation, its value and visibility related.

Suppose aerosol particle size does not change with height, then the aerosol attenuation coefficient is proportional to its concentration. Its relationship with the elevation changes are as follows.

$$\sigma_a(H) = \sigma_a(0)\exp(-\frac{H}{H_0}) \tag{7}$$

$$\tau = \tau_G^{\left[1-\exp(-\frac{H}{H_0})\right]\frac{H_0}{H}} \tag{8}$$

$$\tau_G = \exp(-\beta R) \tag{9}$$

τ is atmospheric transmittance when propagation distance is R on the H high degree. τ_G is atmospheric transmittance when propagation distance is R on the sea. β stands for the attenuation coefficient.

Different conditions of laser atmospheric transmittance were obtained through programmed calculation. Atmospheric transmittance curve of 10.6μm laser which is changed by visibility and propagation distance is drawn. Fig.2 is the 10.6μm laser atmospheric transmittance curve.

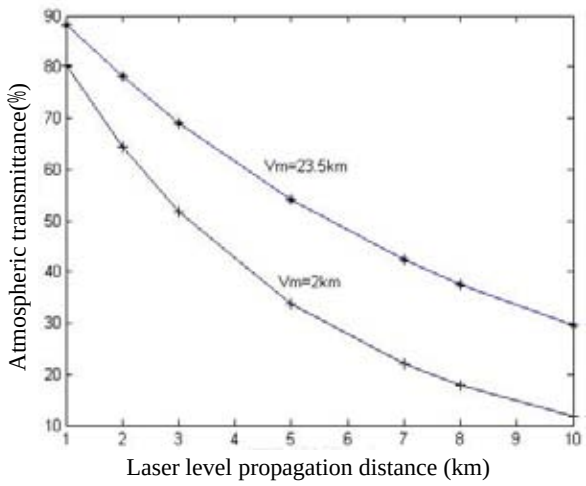

Fig.2. 10.6μm laser atmospheric transmittance curve

D. Results Analysis

Some valuable results are as follows:

1) Suppose that visibility is invariable. The atmospheric transmittance changes slowly when elevation changes.

2) Suppose that elevation is invariable. The atmospheric transmittance obviously increases when visibility increases.

3) Suppose that elevation and visibility are invariable. The atmospheric transmittance obviously descends when propagation distance increases.

4) The atmospheric transmittance of atmospheric propagation on the sea is low. Two methods can be adopted to enhance laser propagation energy. One is that propagation distance is shortened. The other is that laser energy is enhanced. But high-energy laser propagation may arouse non-linearity optical effect [12].

V. EXPERIMENT RESEARCH ON LASER DISTURBING CCD DETECTORS

CCD is the abbreviation of charge-coupled device. CCD was first developed by America's bell LABS in 1970. This kind of device has such advantages as small size, high sensitivity, the dynamic range and so on. CCD has been used widely to weapons guidance, satellite reconnaissance, camera military and civilian many fields[13][14].

Combined with the specific conditions of the laboratory, He-Ne laser disturbing CCD imaging system was accomplished.

A. Eexperimental Facility

In the experiment, CCD is a certain type 1/3 inches target surface black and white miniature camera. Level clarity are 420 line, pixel is 500 (horizontal) x 582 (vertical), light-sensing surface area is 4.9 mm x 3.7 mm, minimum illuminance F = 1.2, sensitivity is 0.05 Lux. Optical lens of view is 52 DHS x 44 DHS, aperture F = 2.0, focal length of the lens is 360 mm, lens material is the quartz glass.

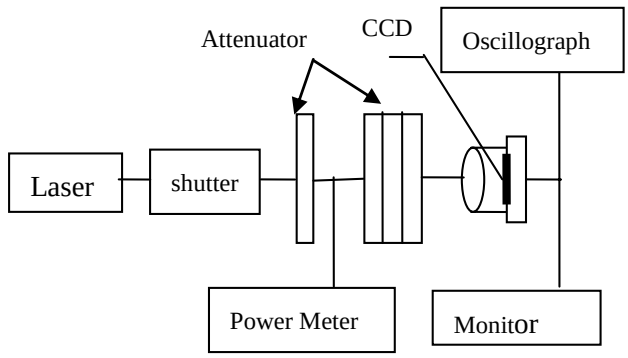

Fig.3. Experiment device sketch of CCD imaging detecting system disturbed by He-Ne laser.

Because the CCD saturation threshold is small, background light effects must also be taken into consideration. In order to reduce the error, the experiment was made in the dark room inside. Fig.3 is the experiment facility. Laser power meter measuring precision is 5%, minimum detection power is pW level. In the experiment

He-Ne continuous laser average power is 25mW. The optical aperture is 4mm.

B. On-axis Laser Disturbing CCD Detectors Eexperimental Results

Laser beam has been adjusted, make the laser beam and CCD detection system axis in line with a light. The distance between laser hole and CCD detector is kept 1.6m. The CCD video output signal and image are respectively observed with an oscilloscope and monitor. The CCD state is judged based on signal waveform and image. CCD detectors work in linear workspace, when the laser power density on the CCD is 6.2 x 10^{-7} W/cm^2, the target surface diameter is about 6μm. Fig.4(a) is the monitor image. CCD detectors work in pixel saturation, when the laser power density on the CCD is 9.8×10^{-7} W/cm^2,. Fig.5(a) is the monitor image. CCD detectors work in saturation, when the laser power density on the CCD is 2.8W/cm^2, Fig.6(a) is the monitor image. Fig.7. is the relationship curve between CCD saturation area ratio and laser incident energy. In order to see details, the abscissa is denoted with the logarithmic, so get Fig.8.

CCD detectors can be effectively disturbed by He-Ne laser through the experiment results. 0.632 um laser array of visible smooth with effective interference, increasing incidence laser power and irradiation time increases, CCD system has been interference area increased. Disturbed area of CCD detectors system will increase with increasing incidence laser power and irradiation time increasing.

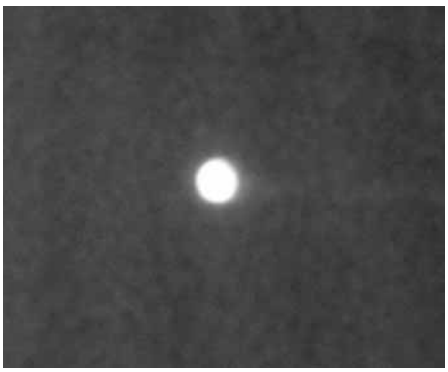

Fig.4. (a) CCD detectors linear working

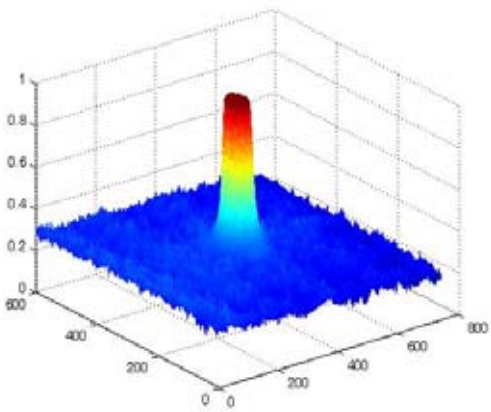

Fig. 4. (b) CCD detectors saturation area ratio

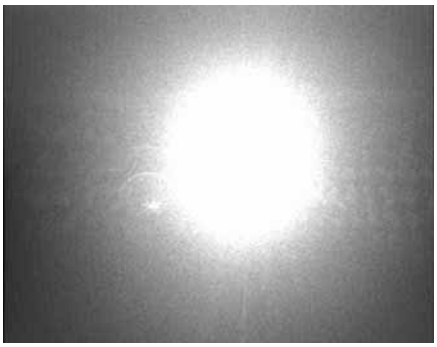

Fig.5. (a) CCD detectors pixel saturation

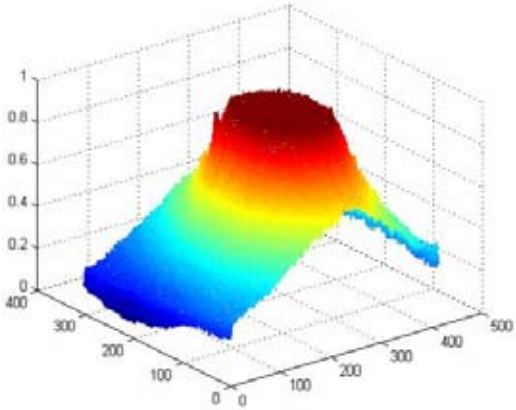

Fig. 5 (b) CCD detectors saturation area ratio

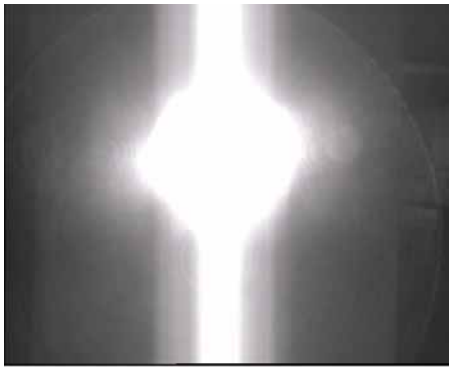

Fig.6. (a) CCD detectors saturation

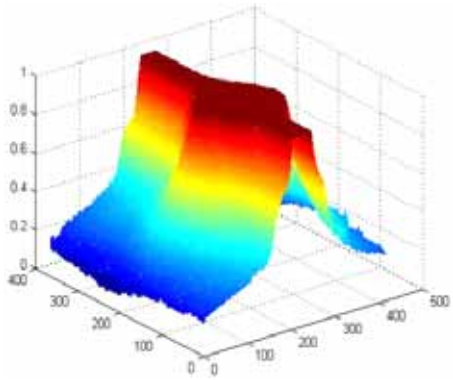

Fig. 6 (b) CCD detectors saturation area ratio

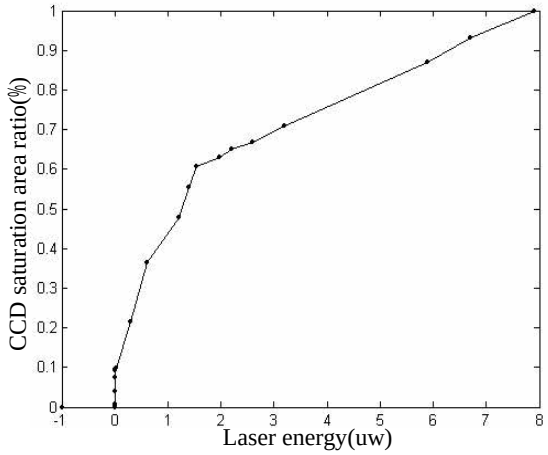

Fig.7. Relationship between CCD saturation area ratio and laser incident energy

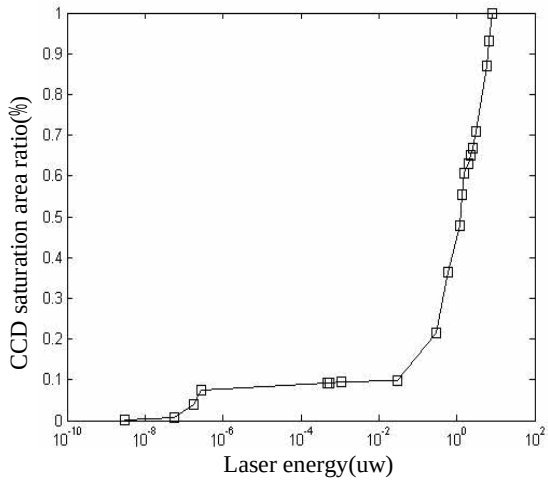

Fig.8. Relationship between CCD saturation area ratio and laser incident energy

C. Off-axis Laser Disturbing CCD Detectors Eexperimental Results

When the distance between detectors and the goal is so far, the angle of view is small. Sometimes the laser only exposes the detector optical window the surface. Laser is not able to enter detector's field of view. So off-axis laser disturbing CCD detectors is also an important problem[15].

The related experiment was carried only qualitatively. The laser output power is invariable in the experiment. Laser incidence CCD detector's angle is changed. Jamming images are gathered through the camera. The relationship between CCD saturation area ratio and laser incident angle was counted.

Laser beam has been adjusted; make the laser beam and CCD detection system off-axis. The distance between laser hole and CCD detector is kept 1.2m. The CCD video output signal and image are respectively observed with an oscilloscope and monitor. CCD detectors work in saturation, when the laser power density on the CCD is 1.38×10^{-1}W/cm^2. The angle between incident laser and the CCD detector optical center optical axis was increasing from 5 ° to 28 °, jamming images are gathered through the camera. Jamming images are processed with computer. The relationship curve between CCD saturation area ratio and laser incident energy is drawn. Fig.10 is the relationship curve.

The experiment results indicate that when the laser power is certain, laser disturbing effect becomes weak with included angle enlargement. CCD detectors can be effectively disturbed by off-axis laser.

Fig.9 CCD detectors linear working

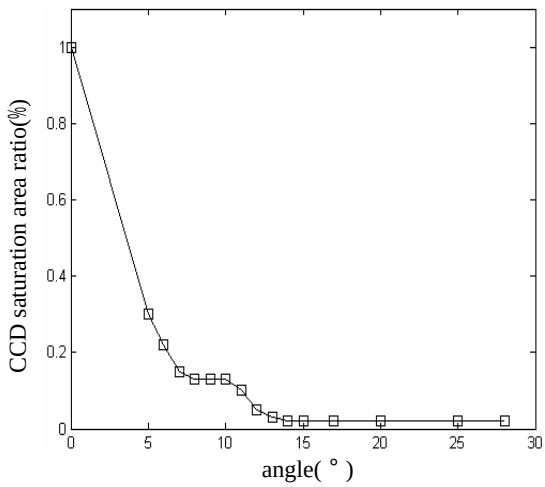

Fig.10 Relationship between CCD saturation area ratio and laser incident energy

VI. ESTIMATION OF LASER ENERGY WHICH CAN DISTURB EFFECTIVELY IR DETECTOR

When laser energy is bigger than its destruction threshold, IR seeker has no signal output. Guidance law is invalid. So missile is effectively disturbed. 1.06μm laser irradiating IR detector was given as an example.

A. Estimation of the Target Surface Laser Spot Size

R stands for distance between laser and IR detector. a stands for the proliferation of missile laser spot radius, which is aroused by diffraction.

$$a = R\theta \tag{10}$$

θ stands for tracking system accuracy, θ_y stands for divergence angle of laser beam diffraction, θ_d stands for laser light source jitter angle.

$$\theta = \left(\theta_y^2 + \theta_d^2\right)^{1/2} \tag{11}$$

$$\theta_y = 1.22\frac{\lambda}{D_0}\beta \tag{12}$$

λ stands for laser wavelength, D_0 stands for laser launch telescope aperture, β stands for beam quality factor. If takes D_0 =0.4m， β =3， $\theta_d = \theta_y/2$, may extract the laser spot radius in the different distance situation. Table Ⅴ is the results.

TABLE Ⅴ
LASER SPOT RADIUS(CM)

R(km) / D_0 (m)	5	8	10
0.4	5.5	8.7	10.9

B. Estimation of Laser Energy Which Can Disturb IR Detector

In order to facilitate the study of the problems, it is supposed that the laser is always accurate radiating seeker, it is able to guarantee aiming accuracy and stability.

P_0 stands for laser output power, τ_1 stands for atmospheric transmission coefficient, τ_2 stands for fairing through coefficient, τ_3 stands for filter through the coefficient, τ_4 stands for modulation plate through coefficient, a stands for the proliferation of missile laser spot radius, D_1 stands for anti-ship missile optical lens diameter, D_2 stands for the detector photosensitive surface diameter, P_0 stands for laser power output. P stands for detector received power density.

$$P = \frac{0.838P_0\tau_1\tau_2\tau_3\tau_4}{\pi a^2}\left(\frac{D_1}{D_2}\right)^2 \tag{13}$$

0.838 is distributed in the Airy pattern first light in the dark rings.

$$P_0 = \frac{P\pi a^2}{0.838\tau_1\tau_2\tau_3\tau_4\left(\frac{D_1}{D_2}\right)^2} \tag{14}$$

Suppose that optical lens diameter D_1 equals to 5cm, the photosensitive detector diameter equals to 4mm, missile fairing transmittance equals to 0.7, filter transmittance equals to 0.7, reticule transmittance equals to 0.5, laser wavelength equals to 1.06 μ m, CCD detector melting damage threshold power density equals to 80 w/cm^2 [16], atmospheric transmittance coefficient is based on the value of the previous study results. When level visibility equals to 23km in the mid-latitudes summer, these data will be substituted for the formula (13), laser energy which can disturb IR detector can be obtained. Table Ⅵ is the results.

TABLE Ⅵ
LASER ENERGY (W)

R(km) / P (w/cm^2)	5	8	10
80	1195	7728	43418

VII. CONCLUSION

1.06μm laser irradiating IR detector was given as an example, laser soft damage to IR seeker was researched. Some valuable data and conclusions were gained. In order to destroy the anti-ship missile effectively, two methods can be achieve. In order to improve the stability of laser points, the precision of laser aiming trace can be improved. Transmit power can be improved through the compression laser divergence angle.

ACKNOWLEDGMENT

This work is supported by the plan project of Shandong provincial education department (No.J08LJ69).

The author is grateful to the Ms. JIN Xin for her warmth help in this paper.

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Yanwu Liu was born in1977. He is an instructor of the School of Information and Electronic Engineering, Shandong Institute of Business and Technology. He received the bachelor and master degrees in signal and information processing in 2001, 2004, respectively. His research interests are signal processing and electro optical countermeasures.