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The characterization of laser-induced thermal damage mechanism of mid-infrared optical coatings with surface contaminants

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Abstract

Understanding the laser-induced thermal damage mechanism is important to the development of high power continuous wave (CW) laser. In this paper, we monitor the evolution of damage via a self-build optical element testing platform and build a correspond theoretical model based on the temperature field and heat conduction theory. The waveband of optical coatings (ZnSe and YbF_3) under test is dedicated for the mid-infrared. Using a 10 kW level mid-infrared CW laser, the thermal stress damage process of the optical coatings caused by surface contaminants is recorded. The Finite Element Method was employed to calculate the thermal damage mechanism of mid-infrared optical coatings. The calculated thermal damage mechanism agrees very well with our experiment. To the best of our knowledge, this is the first comprehensive study on thermal damage mechanism of mid-infrared coatings with surface contaminants induced by CW laser.

Keywords: laser induced damage, thermal damage process, optical coating, contaminats

(Some figures may appear in colour only in the online journal)

1. Introduction

In high power and energy laser system, optical coating is an indispensable component. Laser induced damage of these optical coatings becomes a troublesome issue, which deeply influences the robustness of the whole laser system [1]. Under the irradiation of high power continuous wave (CW) laser, the thermal effect is the main origin of the damage when the laser interaction occupies for a long time [2, 3]. There are many factors causing the thermal damage of the optical coatings, such as substrate flaw, coating defect and surface contaminant [4–6]. Among them, surface contaminant has the major effect for thermal damage which could lead to a serious absorptivity peak. The optical coatings normally were polluted by contaminants in the procedure of manufacture, storage, transportation and use. Despite the optical elements are sufficiently cleaned before use, they are still very likely to be contaminated during the later application. These factors brings lots of difficulties for the contaminant prevention. Therefore it is necessary to study the influence of contaminants on top. The contaminants on the surface of optical coatings may cause reflection degradation [7] and absorptivity peaks. Under the irradiation of high energy CW laser, these areas with absorptivity peaks will absorb plenty of laser energy and result in the rise of temperature. Once the temperature increase to the critical ablation value, the optical coatings

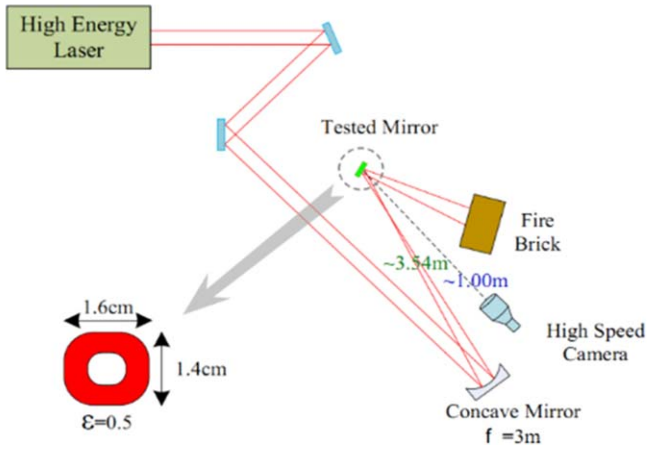
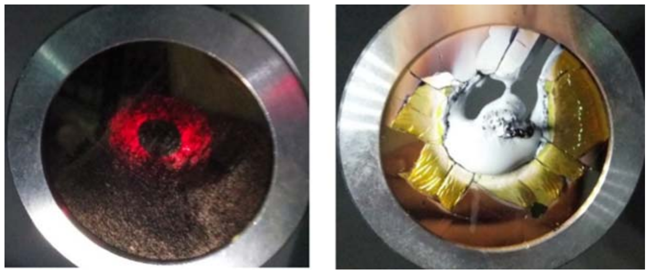


Figure 1. The experiment setup [13].



(a) The contaminated high reflective mirror.

(b) The high reflective mirror damaged by high energy CW laser.

Figure 2. The contaminated high reflective mirror before and after irradiation.

(ZnSe and YbF_3) begin to ablate [8]. Then the damage area will continue to extend and eventually lead to the catastrophic damage in whole laser system [9].

Therefore, it is essential to measure the absorptivity distribution of optical coatings with surface contaminants when we study the thermal damage mechanism. This is difficult, especially for the mid-infrared optical coatings with low absorptivity. In our previous work, we have set up a system to measure the low absorptivity distribution of mid-infrared optical coatings [10]. Here we continue to study the influence of the other factors, especially the surface contaminants. The study on the influence of surface contaminants is still not fully understood [11]. In this paper, we focused on the thermal damage process mainly caused by surface contaminants. Firstly the thermal damage process of mid-infrared optical coating was recorded by a self-build optical element testing platform. In order to better analyze the damage mechanism, we measured the critical ablation value of mid-infrared optical coatings. Together with the absorptivity distribution of surface, a theoretical model based on the heat conduction theory was established [12] The calculated thermal damage mechanism of the optical coating agrees very well with the experimental data. As far as we know, this is the first comprehensive study on thermal damage mechanism of mid-infrared optical coatings with surface contaminants induced by CW laser.

2. Experimental setup and result

In this paper, an optical element testing paltform is established, by which the thermal damage process of the contaminanted optical element is recorded, which has also been reported in our previous work [10]. Therefore, here we only give a brife introduction. The testing platform is based on a 10 kW level high energy DF laser, as shown in figure 1 [13]. The output beam from the high energy laser is converged by a concave mirror ($f = 3$ m). The tested mirror is located behind the focal spot of the concave mirror and it is irradiated by the contracted beam. The laser intensity pattern on the tested mirror is illustrated in figure 1, which is a ring shape. The side length of the laser spot is 1.6 cm long and 1.4 cm width. The obscuration ratio is 0.5 and the area of the laser spot is 1.5 cm^2. The power density of laser irradiated on the tested mirror is 6.8 kW cm^{-2}. During the irradiation, we use a high speed camera (frame frequency: 40 000 fps, exposure time: 25 μs, FASTACAM-SA4, Photron Inc.) to record the evolution of the damage. The optical element irradiated by laser in the experiment is a high reflective mirror as shown in figure 2(a). The radius of the optical coating is 2.5 cm. The thickness of coating and substrate is 12.1 μm and 7 mm respectively. The optical coating consists of ZnSe and YbF_3.

Figure 2(a) shows the contaminated high reflective mirror in the test. In our experiment, the coatings was exposed to the air in storehouse for several days in order to randomly deposite the dust and metal debris on the surface of coatings. Before the test, we had measured the absorptivity distribution of these coatings with surface contaminants by our system [10], which was needed in the later theoretical study. Then without cleaning, we directly put the tested optical elements to the system to recorded thermal damage process with contaminanted. The contaminanted optical coatings has been irradiated by the high energy CW laser for 1.5 s at every turn. Ten contaminanted optical elements are seriously injured one by one in our experiment. Figure 2 shows one of them as a representative. Interestingly, all the damaged elements have a similar final appearance, which is shown in figure 2(b). Finaly, the optical coatings have ablated and the optical elements have broken into several pieces.

In addition, from the recordings, we found these ten trials all had an unexpected similar thermal damage evolution, which has been shown in figure 3 and described as the following.

Firstly, when the high energy CW laser irradiated the element, the contaminants absorbed the laser energy and rose to a very high temperature (∼1700 K) [4]. The contaminats' temperature was so high that they thermally irradiated considerable visible light. Many luminous dots appeared on the coating surface, corresponding to figures 3(a)–(c).

Secondly, with the high energy laser irradiating, some energy flux transferred from contaminants to the coating, which would cause coating temperature rise rapidly. The absorptivity of these contaminants various because of their different shape and size. Therefore, there was always one or

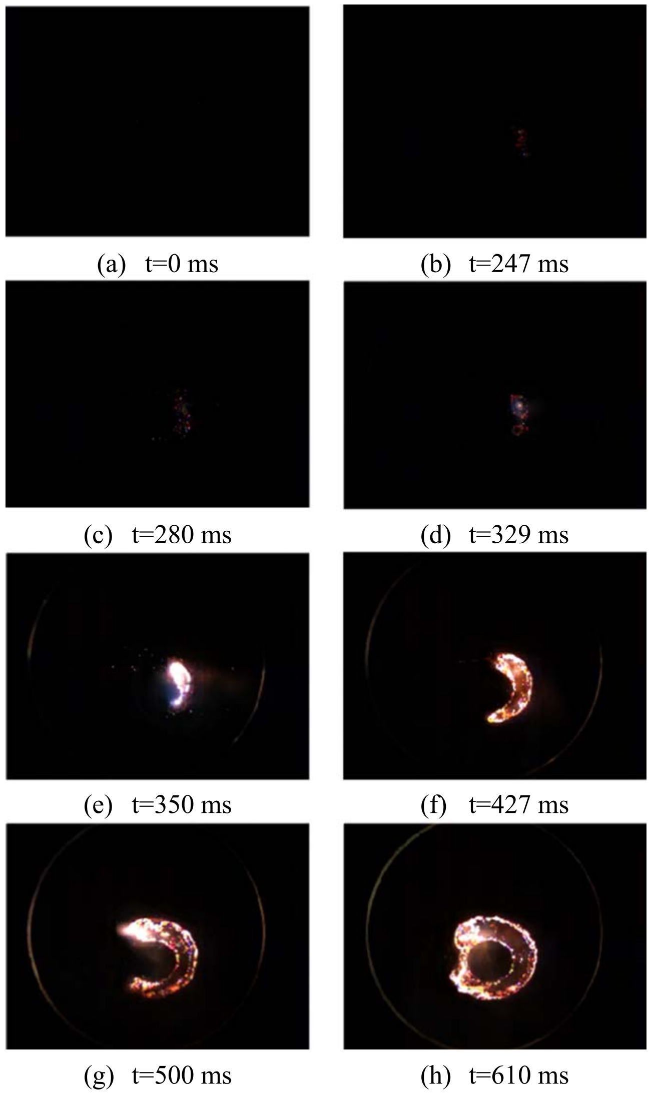


Figure 3. The thermal damage process of optical coating at different times.

more spots in coating whose absorptivity was strongest and the temperature first reached to the critical ablation value of optical coatings (we would measure this value in part three). Then this spot of coating started to ablate. At the beginning, the area of the burnt coating was small, which was as large as the contaminant, corresponding to figures 3(c) and (d).

After that, the substrate at that spot was exposed. Here we should notice that the absorptivity of the coating was very small (<100 ppm for this high reflective mirror) while the absorptivity of the substrate without coating was relatively large (nearly 0.1). That spot with burnt coating absorb a great deal laser energy and rise to very high temperature. Then the heat conducted from that spot to the surrounding area. If the temperature of surrounding coating reached to the critical ablation value, it would burn too. As a result, the coating burned and quick spreaded from spots to the surroundings. Finally the ablated area expanded from spots to a ring, which was exactly the laser spot,corresponding to figures 3(e)–(h).

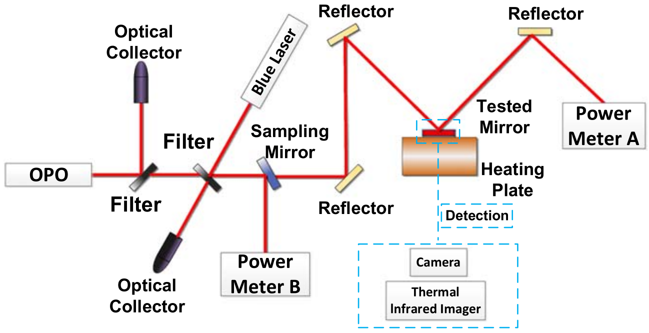


Figure 4. The experiment setup for thermal damage threshold measurement.

3. Critical ablation temperature measure

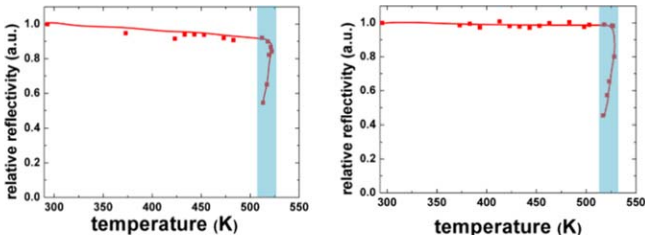
Next, we measure the critical ablation temperature value of coatings, which is essential for us to set up the theoretical model. The optical element consists of two parts, the coating and substrate. The material of coating is ZnSe and YbF_3, and the material of substrate is monocrystalline silicon. The thermal damage threshold of monocrystalline silicon is about 1687 K [14], which is far above the critical ablation temperature value of coatings. In addition, as for materials of ZnSe and YbF_3, the critical ablation temperature value of film and bulk are different. Therefore, we need to measure this value of optical coatings in this system by setting up a testing platform.

Figure 4 shows the measurementing setup we use. In this testing platform, the mid-infrared optical parametric oscillator (OPO) was used for the measurement, whose average output power is 5 W. Only the laser with wavelength of 3.8 μm from the OPO could pass through the filter. In this system, we also used a blue laser for guiding because the laser of OPO are invisable by eyes. The heating plate was used to control the temperature of optical coatings and the thermal infrared imager was used for detection of the tested optical coating temperature. Power meter A receives the laser reflected from the tested mirror. Power meter B receives the sampling laser for eliminating the power fluctuations. The camera records the change of tested optical coatings during the experiment.

In this part, we tested six optical elements. We all found that when the temperature of optical coatings were getting to a critical value (about 523 K), the optical coatings started to desquamate according to the data from camera. And at this temperature, the power of laser reflected from the tested mirror dropped dramatically. We chose two experiments to exhibit the change of relative reflectivity, as figure 5 shows. Therefore, the critical ablation temperature of optical coatings in our experiment is about 523 K.

4. Calculation model and theory

There have been several models using thermal conduction theory to anlysis temperature field of coatings [3, 12]. The camparison between the theory and experiment is still lacking. Mentioned in the above session, we have measured the



(a) Experiment 1 (b) Experiment 2

Figure 5. The change of relative reflectivity over temperature.

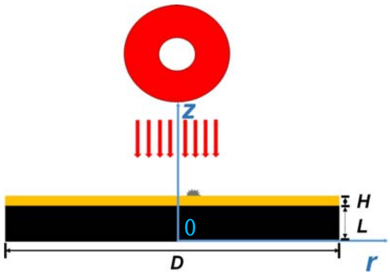


Figure 6. Scheme of the coating model with contaminant irradiated by laser.

critical ablation value of coatings By this value, the dynamic damge procedure of coatings can be analyzed. Meanwhile, what we studied is the mid-infrared optical coatings under the irradiation of CW laser. The study on thermal damage with mid-infrared wavelength laser is insufficient. The study on the influence of contaminants also made this work more innovative.

4.1. Model establishment

A scheme of the optical coating model used for our theoretical research is illustrated in figure 6. H stands for the thickness of the coating. L stands for the thickness of the substrate, D stands for the diameter of the sample. The cylindrical coordinate system is established as follows. The substrate is monocrystalline silicon and the coating consists of ZnSe and YbF_3. The critical ablation temperature of this optical coating has been measured in the above part, which is 523 K. We assume that coating and substrate are isotropic continuous medium and the absorptivity of the laser energy is volume absorptivity. The small change of their thermal parameters with temperature rise can be negligible.

4.2. Analysis model

Because of the relatively long time of CW laser irradiation, the interaction process of laser acting on the coating and substrate is mainly heat transfer process. Surface radiation is negligible and all the laser energy absorbed can be transferred to heat. We suppose the laser beam is incident at the coatings surface ($z = H + L$), as figure 6 shows. The transient heat transfer in the coating/substrate system during laser irradiation can be described by the heat conduction equations as follows [3]:

$$c_i\rho_i\frac{\partial T(r,z,t)}{\partial t} + \nabla\cdot[-k_i\nabla T(r,z,t)] = Q_i(Q_i = 0). \quad (1)$$

In the equation (1), T (r, z, t) stands for the temperature distribution in the optical element at the time point t. The subscripts $i = f, s$ means the coating and the substrate respectively. c_i stands for specific heat capacity, ρ_i stands for density, and k_i stands for thermal conductive coefficient. Q is the source term. In this simulation, we assume the optical component consists of two isotropic continuous mediums, the coating and the substrate. There is no source term in optical coatings under laser irradiation.

Equation (2) is the initial condition as follows. T_0 is ambient temperature, which is taken as 293 K. Between the optical coating and substrate, the thermal properties would change dramatically. Therefore, there would be a joining condition in equations (3) and (4) to keep the heat flow continuous.

$$T(r,z,0) = T_0(T_0 = 293\text{ K}) \quad (2)$$

$$k_f\frac{\partial T_f}{\partial n_f} = k_s\frac{\partial T_s}{\partial n_s} \quad (3)$$

$$-k_f\frac{\partial T_f}{\partial n_f} = h_{fs}(T_f - T_s). \quad (4)$$

In the equations (3) and (4), h_{ij} is the interface heat transfer coefficient. The inverse of h_{ij} is interfacial thermal resistance. Because the thermal properties differ a lot between optical coating and substrate, the interfacial thermal resistance cannot be ignored. In the model, we simulate the interfacial thermal resistance by introduce a physical layer of thermal resistance.

The optical coatings are heated on the upper surface by heat flux q which is caused by the laser irradiation. The heat flux q is introduced by the boundary conditions in equation (5) [3].

$$-\vec{n}_z\cdot[-k_f\nabla T(r,z,t)|_{Z=H+L}] = q. \quad (5)$$

In addition, on the irradiated surface of film, the heat flux q represents the annular heat flux induced by the CW laser with the influence of contaminants on the film surface. The heat flux can be expressed as follows [12].

$$q = I\cdot\Gamma(t)|_{t=0}, \quad (6)$$

where I represents the space and time distribution of laser beam. $\Gamma(t)|_{t=0}$ is the absorptivity distribution of coatings with surface contaminants, which can be measured by the system we set up before [10]. It was noticeable that what we measured was exactly the coatings used in above experiments in part two. Therefore $\Gamma(t)|_{t=0}$ contains the information about surface contaminants' size and location in reality.

Actually the $\Gamma(t)|_{t=0}$ measured is only an initial value. The absorptivity distribution Γ varies with the temperature distribution T of coatings in the whole process. When the temperature in certain spot reaches the critical ablation value (523 K), the contaminated optical coating starts to ablate slightly, leading to the exposure of substrate. Then the absorptivity in this area will increase dramatically because the

Table 1. Parameters of optical coatings used in the calculation.

Item	Value	Unit
Melting point of film T_{ablation}	523	K
Thermal conductivity of film c_f	18	$\text{W m}^{-1}\text{ K}^{-1}$
Thermal conductivity of substrate c_s	140	$\text{W m}^{-1}\text{ K}^{-1}$
Density of film ρ_f	4967	kg m^{-3}
Density of substrate ρ_s	2329	kg m^{-3}
Specific heat capacity of film k_f	344	$\text{J kg}^{-1}\text{ K}^{-1}$
Specific heat capacity of substrate k_s	713	$\text{J kg}^{-1}\text{ K}^{-1}$
running time of CW laser τ	1.5	s

absorptivity of substrate without coating is relatively larger. Then the mutational absorptivity distribution Γ will in turn affect the change of temperature distribution T. Therefore, the temperature distribution T and the surface absorptivity distribution Γ are dependent upon one another as time goes on.

This interactive process repeats over and over again as time goes until the coating burns out. We can use this iteration between the temperature distribution T and the absorptivity distribution Γ to study the damage process and get the theoretical results.

4.3. Calculation parameters

In this calculation, the heat flux on the surface of coatings irradiated by CW laser is 6.8 kW cm^{-2}. The output beam of unstable cavity is annular beam, which is shown in figure 1. The size of laser spot is the same as that in the experiment. Radius of the optical coatings is 2.5 cm. The thickness of films and substrate are 0.1 and 7 mm. Table 1 shows the summary of parameters [15] used for calculations and analysis.

5. The comparison of results

In this experiment, we have recorded the thermal damage process of the optical coating caused by contaminants. The optical coating burns out in 610 ms. In addition, we also calculated the thermal damage process with the theoretical model above. Here we compare the results between calculation and experiment.

As figure 7 shows, the left series black background is the damage process observed in experiment, and the right series with blue background is the calculation results. For the calculation results, we display the area where the temperature exceed critical ablation value (523 K) with yellow and red colors.

The subgraphs in figure 7 exhibit the appearance of the element at different point of time with 1.5 s irradiation. The high energy CW laser is turned out at $t = 0$ ms.

From the results, we can find that the calculated thermal damage process of coating is in agreement with the experimental data. We had studied ten trials in our experiment, and the results all had a similar thermal damage process with our theory model. The ablated area of coatings all expanded from

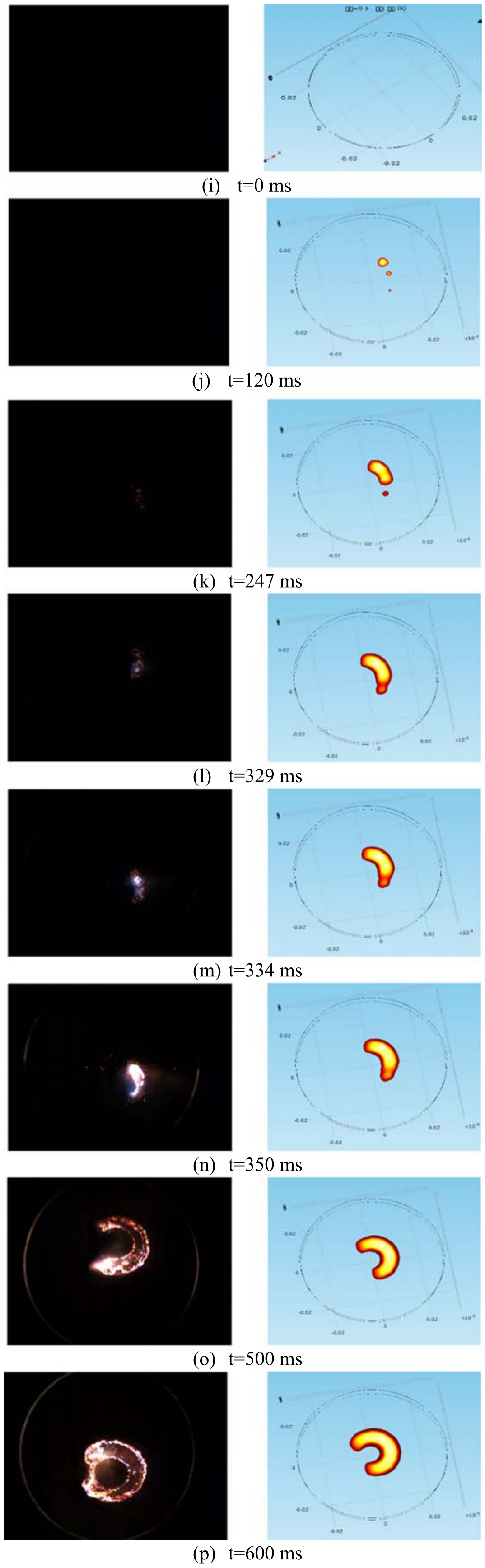


Figure 7. The comparison of damage process between calculation and experiment.

spots to a ring, which was exactly the laser spot. And the irradiated area nearly burns out in about 610 milliseconds. Therefore we can model the thermal damage process as it repeat. This work may be of great help for damage prevention of the optical elements.

6. Conclusion

In conclusion, we demonstrated an experiment by a self-build optical element testing platform to record the thermal damage process of optical coating induced by contaminants. In order to analyze this process, we first measured the critical ablation temperature of optical coatings (523 K). According to the value and absorptivity distribution measured before, we set up a theoretical model based on the temperature field theory and heat conduction theory. The theoretical thermal process was calculated. And the calculated results was in great agreement with our experiment record.

The results showed our success of modeling calculation and experiment in the thermal damage process caused by contaminants. The study on the thermal damage mechanism of mid-infrared optical coatings is insufficient till now. What we studied is exactly the mid-infrared optical coatings (ZnSe and YbF_3) under the irradiation of CW laser. The study on the influence of contaminants made this work more innovative. To the best of our knowledge, this is the first comprehensive study on thermal damage mechanism of mid-infrared coatings with contaminants induced by CW laser. The physical model was established and experiment was observed for the first time till now. This work can be helpful for the theoretical research of the CW laser induced thermal damage. Moreover, it can help us better understand the influence of contaminants and prevent the optical elements from thermal damage in high power laser system.

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