Optik 121 (2010) 1735–1738

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Research on temperature field characteristics of optical films under 1064 nm short-pulse laser radiation

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ARTICLE INFO

Article history:
Received 8 December 2008
Accepted 21 April 2009

Keywords:
Short-pulse laser
Optical films
Film temperature field distribution

ABSTRACT

The 3-D temperature field distribution (TFD) equation of optical films (OFs) was analyzed, based on the film temperature field distribution (FTFD) model irradiated by Gaussian short-pulse laser, and short-pulse laser-induced temperature field distribution of TiO_2/SiO_2 composite membranes on K9 glasses was obtained by means of numerical simulation. The results show that the thermal effect of optical films is very obvious under the Gaussian short-pulse laser. Temperature at the center of the spot rises faster than in other areas, and it decreases along the radius rapidly. It provides theoretical basis for progress analysis of short-pulse laser acting on optical films.

1. Introduction

Laser-induced damage optical films is a primary study coverage of laser antagonizing optoelectronic system. Under the condition in which detection system is shutting down, laser-induced damage films of optical elements can invalidate the detection performance of the system. They can even disturb and damage the optoelectronic system.

When the target is far from the optical source, because of the effects of the atmosphere, the spot radiating to target will enlarge and some phenomena such as optical breakdown, material ionization, plasma production and so on are hard to occur, but the OFs will rupture or abscise due to their optical energy absorption.

Under laser radiation, laser energy is absorbed by OFs and heat is deposited on them [1,2]. Temperature gradient is formed as the deposited heat diffuses continuously by means of heat conduction and heat emission, and then a non-uniform temperature field develops in films. Under the action of non-uniform temperature field and deformation constraint, there is thermal stress in films, and it is the action of heat-stress coupling which causes films deform and the damage. As the pulse time action is short, the thermal absorption is non-homogeneous. Films' temperature rise unevenly, and the thermal stress overruns the ultimate strength, which causes OFs to break easily. Thus, the temperature field distribution of laser-induced OFs is the basis of research on the mechanism of laser-damaged OFs.

There are many theories and experimental researches on failure mechanism and damage threshold of laser-induced damage optical films [3–11]. Zi Ming Ge [3] calculated the damage of the optical components induced by the transient longitudinal stimulated Brillouin scattering (SBS), and obtained that the damage threshold of the optical glasses is about 80 GW/cm^2 when using a 1064 nm nanosecond pulse laser. Dawei Zhang et al. [4] studied the absorbance and the laser-damage threshold of HfO_2 films prepared by ion-assisted reaction deposition. Jianke Yao et al. [5] studied the Influence of coating material on laser-damage threshold of TiO_2 films. Yueming Liang et al. [6] simulated laser-induced thin film delamination. Cheng Xu et al. [7] studied the influences of SiO_2 protective layers and annealing on the laser-induced damage threshold of Ta_2O_5 films. Xiquan Chen et al. [8] experimentally compared the laser-induced damage mechanism of the sol–gel SiO_2 with the ion beam sputtering deposition of SiO_2 thin films. Liping Liang et al. [9,10] studied the laser-induced damage resistance of sol–gel-derived ZrO_2–TiO_2 composite high refractive index films. Weijun Zhou et al. [11–13] studied the thermal effect and laser-induced damage of TiO_2/SiO_2/K9 film by 1.06 μm continuous wave laser. But few related on the film temperature field distribution pulsed Gauss laser induced at different times.

SiO_2/TiO_2 complex pellicle with A/HL/G structure usually is used as reflection-reducing coating of optical windows, compared to K9. The absorption coefficient is higher, and thermal conductivity coefficient is lower. Films absorb pulsed laser energy to generate stress pulse in practical work, which leads to delamination of the thin film–substrate interface, and disrupts the photoelectrical systems finally. This paper builds the optical film mold irradiated by Gaussian short-pulse laser, analyzes the

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0030-4026/$ - see front matter © 2009 Elsevier GmbH. All rights reserved.
doi:10.1016/j.ijleo.2009.04.005

characteristics of radial temperature fields of SiO_2/TiO_2 complex pellicle on K9 glass substrate under 1064 nm and Gaussian short-pulse laser at different times by means of Matlab software. The changing rules of temperature caused by Gaussian short-pulsed laser irradiating the optical films are presented.

2. Analysis of temperature field

Fig. 1 shows the optical film model irradiated by Gaussian short-pulse laser. It consists of cylindrical coordinates showing the spot center as the origin and the laser irradiation direction as the z-axis. Let T_0 be initial temperature of the samples.

According to Newton's law of cooling, the heat transfer equation of laser irradiating the multilayer films is [14,15]

$$\rho_n C_n \frac{\partial T(r,z,t)}{\partial t} - K_n \nabla^2 T(r,z,t) = g_n(r,z,t) \tag{1}$$

where n is the number of layers of the films, ρ_n the nth film's density, C_n the nth film's specific heat; K_n the nth film's thermal conductivity, $\nabla^2 = \partial^2/\partial r^2 + (1/r)(\partial/\partial r) + (\partial^2/\partial z^2)$ the Laplacian operator in cylinder coordinate, $g_n(r,z,t) = \Re I(r,t)\beta_n n_i |E|^2$ the nth film's laser-deposited energy in unit time and volume, $\Re$ $I(r,t) = I(t)(e^{-(r/r_0)^2}/\pi r_0^2)$ is the optical intensity distribution of Gauss beam; β_n the absorption coefficient of the nth material, n_n the refractive index of the nth material and $|E| = 27.4\sqrt{I(r,t)}$ is the intensity of laser-induced standing wave field [16].

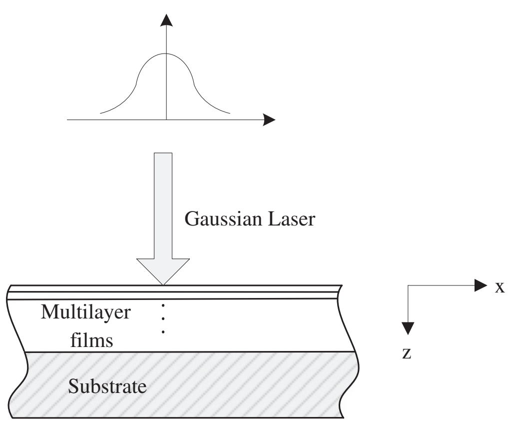

Fig. 1. Laser-irradiating multilayer films.

Due to the fact that temperature rise has finite value in radial and vertical infinite distance, the boundary condition is approximated as follows:

$$\left.\begin{aligned} T(r,z=\infty,t) = T(r=\infty,z,t) = 0 \\ T(r,z,t=0) = 0 \end{aligned}\right\} \tag{2}$$

$$\frac{\partial}{\partial z} T(r,z=0,t) = \gamma T(r=\infty,z,t) = 0 \tag{3}$$

where, γ is the surface thermal transfer coefficient, which relates to the states of surface thermal radiation and thermal convection. One can conclude on FTFD by solving the above equation.

3. Simulation of FTFD

According to the theoretical analysis, the TFD of TiO_2/SiO_2 complex pellicle on K9 glass substrate under 1064 nm Gaussian short-pulse laser at different times was simulated and analyzed based on the semi-infinite model. In the simulation model, let room temperature be 23 °C. The film system structure is A/HL/G and the thickness of each layer is $\lambda/4$. The substrate is a $2 \times 2\,cm^2$ K9 glass. Laser irradiates on the true center of it. Stimulated source is Nd: YAG Q-switched laser, taking into account the damage threshold of TiO_2/SiO_2 films [8,9], the energy of laser output is 100 mJ. Tables 1–3, respectively, give some parameters of K9 glass [11], films [11] and laser.

Using to the boundary conditions (2) and (3), combining classic explicit scheme of partial differential equation and, using difference methods [17], we can solve the heat transfer Eq. (1) with Matlab software, and the FTFD can be simulated.

The 3-D distribution figures of the FTFD can be obtained by rotating 2-D FTFD along T-axis, considering the symmetry of laser-radiated OFs. The distribution figures of the temperature fields at different times can be obtained by changing the time parameters, as shown in Figs. 2–6.

Fig. 2 describes the FTFD with no radiation by laser, which shows that FTFD not radiated by laser is flat everywhere.

Figs. 3–6 describe the FTFD when the film has been radiated 1, 5, 8 and 10 ns, respectively, by Gauss laser. From these figures, it can be seen that temperature at the center of the spot rises very fast and reaches the peak value. This is because the optical intensity at the center of the Gauss spot is much stronger than the spot periphery. The thermal conductivity and bolometric radiation are hard to occur within 10 ns, as enough time is not there for the heat at the center of the spot to dissipate. Therefore, temperature

Table 1
Some optical and thermal parameters of K9 glass (1.064 nm).

Substrate	Density ρ (g/cm^3)	Refractive index (n)	Absorption coefficient β (cm^{-1})	Specific heat capacity C (J/cm^3 °C)	Thermal conductivity coefficients K (W/cm^3 °C)
K9	2.51	1.52	0.01	2	0.014

Table 2
Some optical and thermal parameters of films (1.064nm).

Film layer	Density ρ (g/cm^3)	Refractive index (n)	Absorption coefficient β (cm^{-1})	Specific heat capacity C (J/cm^3 °C)	Thermal conductivity coefficients K (W/cm^3 °C)	Thickness d (nm)
H(TiO_2)	4.26	2.21	18	3	1.8×10^{-4}	120
L(SiO_2)	2.65	1.46	1.3	2	1.7×10^{-3}	184