Theoretical study of laser induced thermal damage on the narrowband filter optical thin film

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Abstract. In the experimental study of the film's thermal damage, an extremely high power density is needed. In order to achieve such high power density, the incident beam is generally converted. In this situation, the cone's angle of the converted beam is inevitable. A narrowband filter optical film is taken as an example. The influence of the beam cone angle on the thermal damage of the optical film is theoretically studied. Under the irradiation of high energy laser, the film absorbs the laser energy and the heat is accumulated continuously in the film. The cone's angle influences the laser intensity distribution, i.e. the heat source, in the multilayer film. The temperature distribution and the temperature rising process are also related to the cone's angle. Only if the cone's half angle is smaller than 3°, the influence of the cone's angle can be ignored.

Introduction

Optical thin film is a kind of important material which is widely used in the field of modern optics, photonics, optical engineering and laser technology [1]. Due to various microstructures, optical thin film is able to spectrally modulate the incident light. The laser induced damage is a crucial factor in the application of optical thin film, which is related to the robustness of the whole laser system. The damage mechanisms of optical thin film have been extensively studied by researchers in theory and experiment [2-6]. There are two types of mechanisms in the damage of optical thin film: thermal effect and field effect, which are responsible for the high energy laser induced damage and the high power laser induced damage, respectively [2]. Under the irradiation of high energy laser, the optical thin film absorbs the laser energy and transfers the laser energy to heat. With the heat accumulating, the optical thin film is likely to fuse and even be totally injured. Because of the very low absorptivity, it needs much high power density (several kW/cm^2) continuous wave (cw) laser to cause damage [2, 5-6]. Considering the difficulty in obtaining extremely high power cw laser in the lab, it usually focuses a relatively low power laser beam to achieve such high power density in the experimental study of the thermal damage process [7-8], as shown in Fig. 1. Nevertheless, the cone angle of the converged beam may influence the heat distribution in the optical film and make much difference on the thermal damage process. In this paper, we took a narrowband filter optical film as an example, and theoretically studied the influence of the beam cone angle on the thermal damage of the optical film.
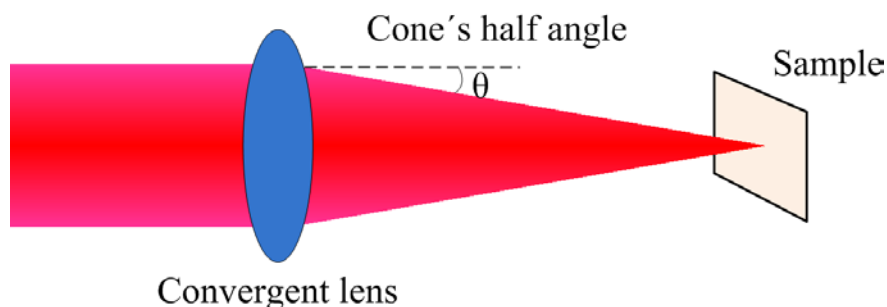

Figure 1 Converged beam with high power density

Mathematical model

A typical optical thin film generally has a multilayer structure, which is composed of two materials with different reflective indexes. The electromagnetic field in the *i*-th layer can be worked out by characteristic matrix, which is expressed as [3],

$$\begin{bmatrix} E_i \\ H_i \end{bmatrix} = \begin{bmatrix} B_i \\ C_i \end{bmatrix} \cdot E_m \tag{1}$$

$$\begin{bmatrix} B_i \\ C_i \end{bmatrix} = \prod_i \begin{vmatrix} \cos \delta_i & j \cdot \sin \delta_i / \eta_i \\ j \cdot \eta_i \cdot \sin \delta_i & \cos \delta_i \end{vmatrix} \cdot \begin{bmatrix} i \\ \eta_s \end{bmatrix} \tag{2}$$

$$\delta_i = \frac{2\pi}{\lambda} \cdot \hat{n}_i \cdot d_i \cdot \cos \theta_i \tag{3}$$

$$\hat{n}_i = n_i - j\kappa_i \tag{4}$$

where, E_i and H_i are the electric field amplitude and magnetic field amplitude in the *i*-th layer; B and C are the normalized elements of the characteristic matrix of a thin-film assembly; δ_i represents the phase thickness in the *i*-th layer; η_i represents the optical admittance in the *i*-th layer; η_s represents the optical admittance in the substrate; d_i is the physical thickness of the *i*-th layer; $\hat{n}_i$ is the complex refractive index of the *i*-th layer and n_i and κ_i are the real part of the refractive index and the extinction coefficient of the *i*-th layer, respectively. The Poynting vector in the *i*-th layer is expressed as .

$$P_i = I_0 \cdot \frac{1}{2} \cdot \mathrm{Re}\left[E_i \times H_i^* \right] \tag{5}$$

in which, I_0 is the intensity distribution of the incident beam. The energy accumulating rate in the *i*-th layer is expressed as,

$$q_i = \frac{4\pi}{\lambda} \cdot \kappa \cdot dP_i(z,t) \Big/ (dz, dt,) \tag{6}$$

As film materials absorb the laser energy, the temperature of the optical film rises constantly. The temperature distribution of the layers is described by thermal diffusion equation. For the the *i*-th layer,

$$C_i \cdot \frac{\partial T_i(z,t)}{\partial t} - K_i \cdot \nabla^2 T_i(z,t) = q_i(z,t) \tag{7}$$

C_i and K_i are the thermal capacity and thermal conductivity of the *i*-th layer, respectively. At the boundary between the adjacent layers, the temperature obeys continuity-condition and the density of heat flow rate obeys conservation law, that is,

$$T_i(z = z_i, t) = T_{i+1}(z = z_i, t) \tag{8}$$

$$K_i \cdot \nabla^2 T_i(z = z_i, t) = K_{i+1} \cdot \nabla^2 T_{i+1}(z = z_i, t) \tag{9}$$

The temperature distribution of the multilayer film can be obtained by formula (1) - (9). Here, a narrowband filter film is taken as an example, which is composed of two film materials: HfO_2 and SiO_2. The reflective index of HfO_2 is larger than SiO_2, hence HfO_2 is denoted as **H** and SiO_2 is denoted as **L** for short. The stack formula of the film is assumed as (**HL**)^8(**LH**)^8**L**. The substrate is assumed as fused quartz. The optical thicknesses of the **H** layer and **L** layer are all a quarter of the wavelength. In the case that the wavelength of incident beam is 1064nm, the physical thickness of **H** layer is 129.1nm and the physical thickness of **L** layer is 185.5nm [9]. The multilayer structure of the optical thin film is s shown in fig. 2.
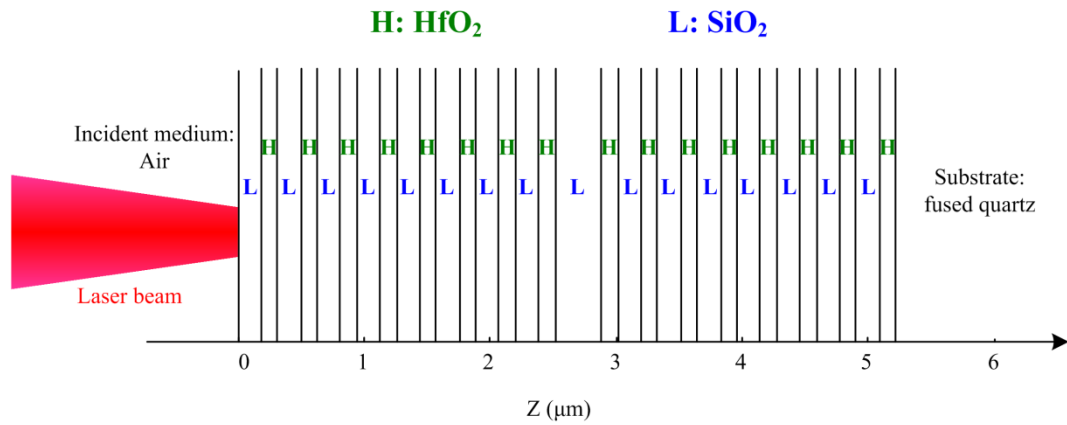
Figure 2 The multilayer structure of the narrowband filter optical thin film

Calculations and Results

The cone angle of the beam influences the laser power distribution (i.e. the heat source) in the multilayer film. Consequently, the temperature distribution is dependent on the cone angle. The laser power distribution and the temperature distribution are calculated at various incident cone angles. In the analysis, the optical parameters and the calorific parameters of the materials are shown in table 1 [10-11].

Table 1. The optical parameters and the calorific parameters of the materials

Material	Heat capacity J/(kg•K)	Thermal conductivity W/(m•K)	Density kg/m^3	Reflective index	Extinction coefficient
Substrate: fused quartz	740	10.4	2.2×10^3	1.465	2×10^{-6}
H layer: HfO$_2$	287	7.7×10^{-4}	9.099×10^3	1.936	2.3×10^{-5}
L layer: SiO$_2$	740	0.28	1.98×10^3	1.475	2×10^{-6}
Incident medium: Air	1008	2.62×10^{-2}	1.165	1	0

According to formula (1)-(4), the spectral transmissivities of the narrowband filter at various cone angles are figure out, which is shown in Fig. 3.
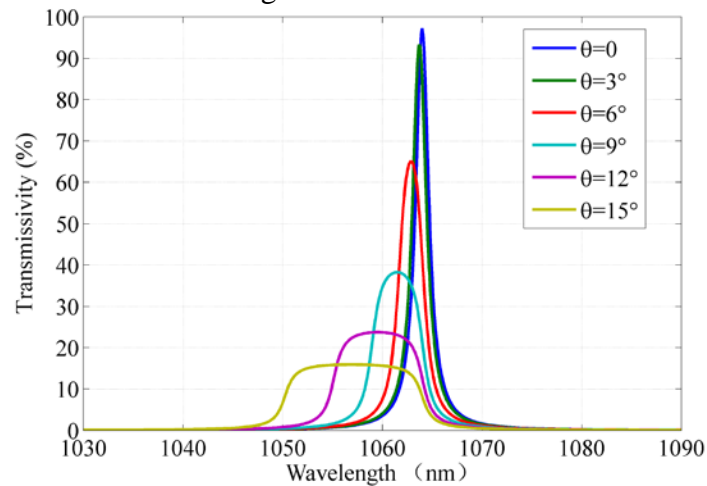

Figure 3 Transmissivity of the narrowband filter optical thin film at various cone angles

As shown in Fig. 3, the transmissivity of the narrowband filter film is seriously dependent on the cone angle of the incident beam. As long as the cone's half angle is smaller than 3°, the spectral transmissivity nearly maintains the characteristic of narrowband pass and the peak transmissivity doesn't fall too much. When the the cone's half angle is increased to ~10°, the bandwidth of the film is expanded a lot, and the peak transmissivity falls below 40%. In a word, the spectral transmissivity is greatly related to the cone angle of the incident beam.

In the condition of different cone angles of incident beam, the intensity distributions of the laser in the multilayer film are also quite dissimilar. The intensity distributions of the laser in the multilayer film can be calculated by formula (1)-(5). The result is shown in Fig. 4.

a. $\theta=0°$ b. $\theta=3°$
c. $\theta=6°$ d. $\theta=9°$
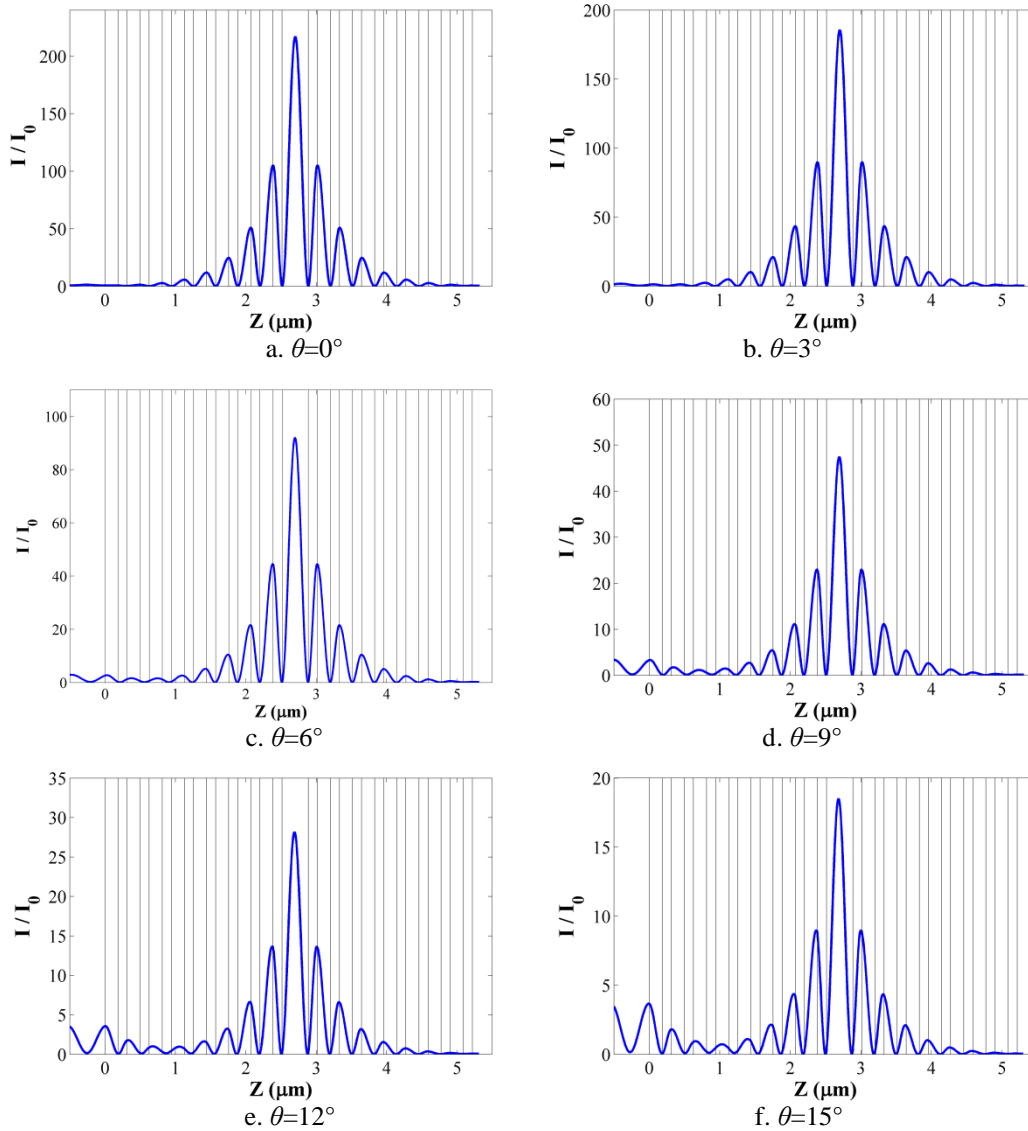e. $\theta=12°$ f. $\theta=15°$

Figure 4 Normalized intensity distribution in the multilayer film

For the narrowband filter film, there are many intensity peaks and intensity troughs at the boundaries between the adjacent layers, as shown in Fig. 4. The maximum intensity appears in the "resonator", that is the thickest layer (2L: SiO_2) here. When the cone's half angle is 0, i.e. parallel incidence, the maximum intensity in the film is more than 220 times of the incident intensity. As the cone's angle increases, the intensity in the film diminishes continuously. When the cone's half angle is 15°, the maximum intensity in the film decreases to 19 times of the incident intensity. In the optical film, the absorbed laser energy heats the film as a heat source. Obviously, in the case of large cone angle, the absorbed energy is much smaller and the temperature will also be smaller than the case of parallel incidence. The temperature distributions in the multilayer film are calculated by the formula (1)-(9), and the results are shown in Fig. 5. The intensity of the incident laser is assumed to be

10kW/cm^2 and the initial temperature of the film is assumed to be 293.15K. The calorific parameters of the film materials are shown in table1.
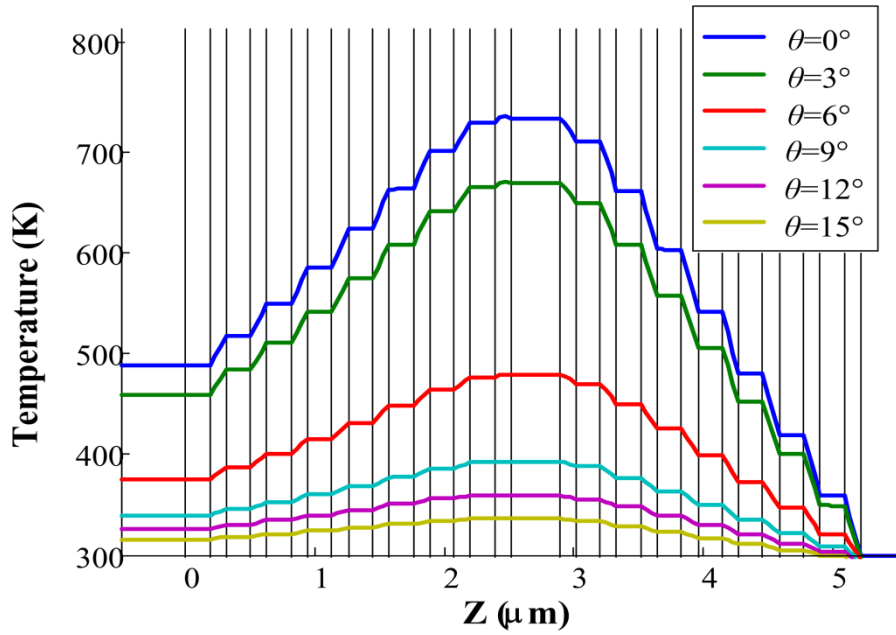

Figure 5 The temperature distribution in the multilayer film irradiated 0.1s by 10kW/cm^2 laser

Fig. 5 gives the temperature distribution in the multilayer film at various cone's angles, which is irradiated 0.1s. From Fig. 5, we can see that the temperature of the middle layer is the highest. The peak temperature goes up to ~720K in 0.1s, when the film is irradiation by parallel beam. In contrast, when the cone's half angle is 15°, the maximum temperature only increases to ~330K. That is to say, the temperature of the film rises slower with larger cone angle of the beam. In addition, the temperature distribution in the multilayer film is not smooth. The **L**: SiO_2 layers reach thermal equilibrium in 0.1s, because their thermal conductivity is so large. The temperature distributions in the **H**: SiO_2 layers are not uniform, because their thermal conductivity is small and blocks the heat exchange.

Moreover, the temperature rising trends of the middle layer are theoretically analyzed, as the film is irradiated by beams of various cone angles. The result is shown in Fig. 6.
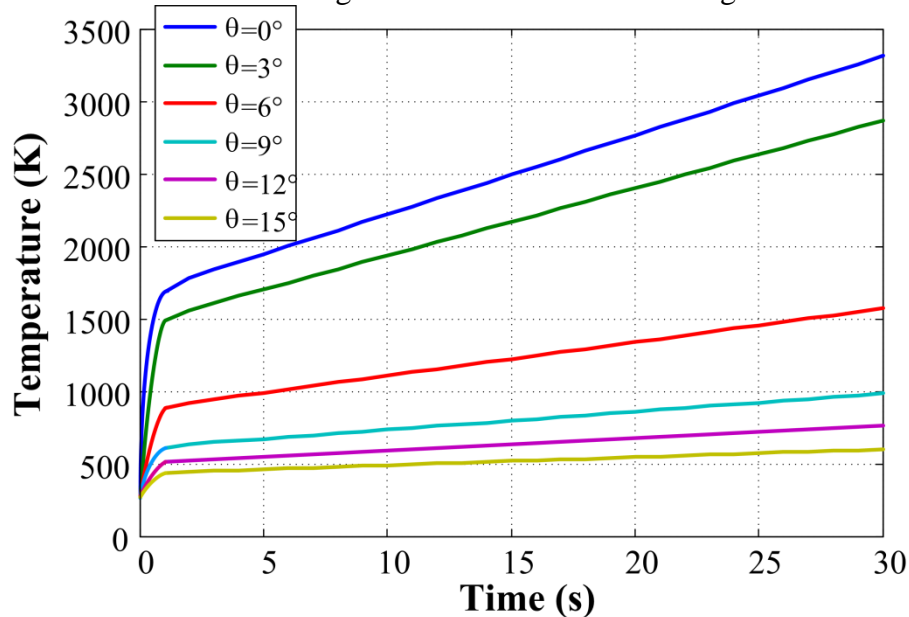

Figure 6 The temperature rising trends of the film at various cone angles

As shown in Fig .6, the temperature climbs very fast when the film is irradiated by parallel beam. In 30s, the temperature of the film reaches ~3300K. It means that the film will be totally damaged in 30s. If the cone's half angle is 15°, the film's temperature increases very slow. The temperature only

grows to ~600K. The film still works well on this temperature. In a word, the cone's angle of the beam has serious influence on the damage of optical thin film. Large cone's angle considerably reduces the temperature increment of the optical thin film.

Conclusion

In the experimental study of the film's thermal damage, the incident beam is generally converted to achieve high power density (several kW/cm^2). In this situation a cone's angle of the converted beam is inevitable. In fact, the cone angle makes much diffidence on the film's thermal damage process. As is shown in the theoretical results, the cone's angle changes the laser intensity distribution in the multilayer film. It means that the distribution of heat source is dependent on the cone's angle. Consequently, the temperature distribution and the temperature rising process are also related to the cone's angle. Only if the cone's half angle is smaller than 3°, the influence of the cone's angle can be ignored. In the case that the cone's half angle is larger than 6°, the film's damage induced by converted beam is totally different from the damage induced by parallel beam.

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