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Analysis on laser-induced transient damage behavior in multilayer coating

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ABSTRACT

Based on the ionization theory and the Drude model of free electron gas, transient damage principle of the anti-reflection coating under ultrashort pulses are analyzed. Specifically, the damage of an anti-reflection coating designed by ZnS/SiO_2 materials is calculated. The results show that during the irradiation process the parameters, such as the refractive index, the electric field and the free electron density, should impact on each other. The coupling relationship between these parameters causes the change in the refractive index, which further leads to the decrease of transmittance of anti-reflection coating from 0.96 to 0.01. In addition, the coupling relationship causes the repartition of free electron density constantly, which eventually leads to the external damage of anti-reflection coating.

1. Introduction

Multilayer coatings are applied to many optical elements to improve the optical properties. Unfortunately, they are the weakest part in an optical system when laser damage resistance is concerned. Their damage resistance will directly affect the application of entire optical system. With the rapid development of ultra-short pulse technology, more strict requirements are put forward on the laser damage resistance of multilayer coatings due to the highly concentrated energy in time domain. Therefore, to analyze the damage characteristics of multilayer coatings is meaningful for improving the damage threshold of whole optical system.

With the development of chirped pulse amplification (CPA), studies of damage under ultra-short laser pulses are carried out. In 1990s, using the impact ionization and photoionization theory, Du and Stuart analyzed the nanosecond-to-femtosecond laser-induced breakdown in fused silica [1–3]. Subsequent damage researches are carried out in multilayer films with the impact ionization and photoionization theory. Among these damage researches of films, the damage threshold dependence of electric field has aroused great interest [4–8]. And a latest development of researches is the considering of electric field repartition when calculating the damage threshold [9]. Specifically, Laurent Gallais pointed out that the growth of free electrons induced by ultra-short pulse will cause change in the refractive index, which will lead to repartition of the electric field. Therefore, the refractive index correction should be considered when calculating the damage threshold.

The previous studies of laser-induced damage of multilayer coating is mainly focused on high-reflection coating, rarely focused on antireflection coating. In the most detection system, multilayer coating is served as antireflection coating to improve response of optical detection system. During the irradiation of an ultra-short laser pulse, the strong incident electric field will increase the number of free electrons by photoionization and avalanche ionization. The growth of free electron density will change the refractive index of materials. These changes in complex index will lead to modifications of the electric field repartition, and further lead to variation in the free electron density [10–11]. In this paper, given the basic characteristics of ZnS and SiO_2 materials [12], a study on antireflection coating designed by ZnS/SiO_2 materials is carried out. The variation of the free electron density has been calculated. Meanwhile, the correction of refractive index and the modifications of the normalized electric field intensity during the above process have been analyzed in detail.

2. Basic theory

2.1. The breakdown of material induced by avalanche ionization and photoionization

When irradiated by ultra-short laser pulses, the electrons in dielectric media can be excited up to the conduction band via avalanche ionization and photoionization. The free-electron

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generation in dielectrics can be described as [10]:

$$\frac{d\rho(t,Z)}{dt} = (R_{PI} + R_{AI}\rho)(1 - \rho/\rho_1) \tag{1}$$

Where $\rho(t)$ is the free electron density in conduction band. The factor $1-\rho/\rho_1$ is the exhaust of valence electrons. ρ_1 is the initial density of valence electron. R_{AI} is the electron avalanche rate [13], R_{PI} is the photo-ionization rate calculated by Keldysh theory [14,15].

Combined with the initial condition of $\rho(t=0)=\rho_0$, the variation of free electron density can be calculated by solving Eq. (1). The parameters used in the calculation of photo-ionization rate and electron avalanche rate are shown in Table 2.

With the increasing of irradiation time t, the free electron density of dielectric media accumulates. When the density accumulates to critical value ρ_c, the phenomenon of plasma flash appears with the dielectric constant of materials mutating. As a result of the plasma flash, the material's refractive index increases and transmittance decreases quickly. This phenomenon is regarded as the symbol of laser-induced damage in dielectric media.

2.2. Calculation of electric field in multilayer coating

In Eq. (1), R_{AI} and R_{PI} are both functions of electric field E. Therefore, it is necessary to calculate the electric field distribution of multilayer coating by Maxwell's equations.

Fig. 1 shows an X-1-layer structure which is irradiated by laser pulse. Starting at the substrate with $k=1$, the layers are numbered in increasing order. The kth layer has thickness z_k, refractive index n_k. The laser is propagating through the multilayer coating in the direction of Z. Based on the Maxwell equations, the electric field $E_k(Z)$ and the magnetic field $H_k(Z)$ in Fig. 1 are calculated by Eqs. (2) and (3) [16].

$$\begin{aligned} E_k(Z) = A_1^{(k)}(&\exp\{-i[2\pi n^{(k)}/\lambda_0](Z - \sum_{j=k+1}^{X+1} z_j)\} \\ &+ A_2^{(k)}\exp\{+i[2\pi n^{(k)}/\lambda_0](Z - \sum_{j=k+1}^{X+1} z_j)\}) \end{aligned} \tag{2}$$

$$\begin{aligned} H_k(Z) = n^{(k)}A_1^{(k)}(&\exp\{-i[2\pi n^{(k)}/\lambda_0](Z - \sum_{j=k+1}^{X+1} z_j)\} \\ &- A_2^{(k)}\exp\{+i[2\pi n^{(k)}/\lambda_0](Z - \sum_{j=k+1}^{X+1} z_j)\}) \end{aligned} \tag{3}$$

In the above equations, take the thickness of air layer z_{X+1} as zero. Coefficients $A_1{}^{(k)}$ and $A_2{}^{(k)}$ are determined by refractive index and thickness of the kth layer. $A_2{}^{(k)}$ can be given below:

$$\begin{aligned} A_2^{(k)} = \downarrow &\frac{[n^{(k)} - n^{(k-1)}]/[n^{(k)} + n^{(k-1)}] + A_2^{(k-1)}}{1 + \{[n^{(k)} - n^{(k-1)}]/[n^{(k)} + n^{(k-1)}]\}A_2^{(k-1)}} \\ &\downarrow\times \exp\{-i[4\pi n^{(k)}/\lambda_0]z_k\} 2 \le k \le X+1 \end{aligned} \tag{4}$$

Since the reflected component of light in the substrate is zero, we can start with $A_2{}^{(1)}=0$. Other A_2 can be calculated successively from Eq. (4). Once the coefficients A_2 are calculated, we can obtain A_1 according to the theory of continuity of the electric field.

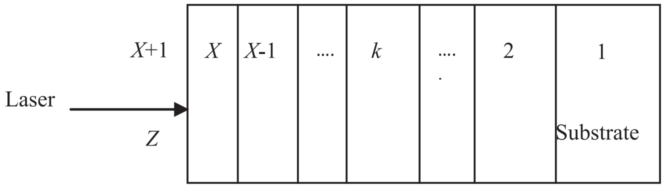

Fig. 1. The model of multilayer coating with laser irradiation.

$$\begin{aligned} A_1^{(k)} = \downarrow &\frac{\exp\{-i[2\pi n^{(k+1)}/\lambda_0]z_{k+1}\}}{1 + A_2^{(k)}} \\ &\downarrow+ \frac{A_2^{(k+1)}\exp\{-i[2\pi n^{(k+1)}/\lambda_0]z_{k+1}\})\}}{1 + A_2^{(k)}} \times A_1^{(k+1)} 1 \le k \le X \end{aligned} \tag{5}$$

$A_1{}^{(X+1)}$ is the incident light amplitude.

By solving Eqs. (2)–(5), $E_k(Z)$ can be calculated recursively. For applying to multilayer coating Eq. (1) can be rewritten as:

$$\frac{d\rho^k(t,Z)}{dt} = (R_{PI}^k + R_{AI}^k\rho^k)(1 - \rho^k/\rho_1) \tag{6}$$

2.3. The correction theory of refractive index

When the free electron density reaches values of 10^{21} cm^{-3}, such electronic densities strongly affect the dielectric function of the material under irradiation. According to the Drude model of free electron gas, the complex refractive index dependence of electronic density can be described below:

$$N(\rho) = \sqrt{n^2 - \frac{\rho e^2}{m\varepsilon_0(\omega^2 + i\omega/\tau_D)}} \tag{7}$$

Where n is the refractive index of the unexcited material, ε_0 is the free space dielectric permittivity, τ_D is the Drude relaxation time with the value of 10^{-15} s [17].

A strong incident electric field will increase the number of free electrons by photoionization and avalanche ionization. The growth of free electron density will change the refractive index of materials. These changes in complex index will lead to modifications of the electric field repartition, and further lead to variation in the free electron density. Considering the complexity of this process, we take the iterative method to calculate the spatial and time distribution of the coupling parameters: Firstly, calculate the initial electric field of antireflection coating by Eqs. (2)–(5).Secondly, calculate the free electron density by Eq. (6).Thirdly, calculate the complex index by Eq. (7). Finally, solve the process iteratively according to the above order. Each iteration time is set to Δt. The process continues until the end of the pulse irradiation.

3. The simulation and analysis

Based on the analyses model introduced above, an anti-reflective coating is employed as the object of study. The anti-reflective coating is a finished product used in a custom-builted detector. And the design of anti-reflective coating is offered by the detector provider.The design parameters are given in Table 1. Table 2 shows the relevant parameters of SiO_2 and ZnS to calculate the free electron density [1,13,18,19].

The incident laser is a Gaussian pulse with wavelength of 650 nm and pulse width of 50 fs, as shown in Fig. 2. The total energy density of laser pulse is 0.18 J/cm^2.The parameter “0.18 J/cm^2” is not based on a practical damage measurement but the theoretical calculations result, which we have verified

Table 1
Design parameters of the anti-reflective coating.

Film stack	λ/nm	n
$G/0.7320L(1.4639H1.4641L)^7$ $(1.4639H1.3420L)(1.22H1.22L)^7$ $(1.22H0.6101L)/A$	650	H–ZnS,$2.35-i2.7\times10^{-4}$ L-SiO_2,$1.46-i2\times10^{-4}$ G-glass,1.52