A new retrieval method of damage defect density in optical thin films

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Received 11 October 2012; accepted 25 September 2017

A new method has been proposed to obtain damage defect density in optical thin films from the differential coefficient of the damage probabilities with respect to the spot size. The retrieval method avoids utilizing the value of defect damage threshold which can’t be measured directly. Firstly, the simulated damage probability curves under some certain irradiated laser fluences have been done by setting damage defect density as $5 \times 10^3$/cm$^2$. Then, the differential coefficient of the damage probabilities with respect to the spot size is done from the simulated damage probability curves. Finally, the calculation of damage defect density has been done by the proposed method. The results show that the calculated defect density agrees well with the set value.

Keywords: Damage defect density, Damage probabilities, Differential coefficient

1 Introduction

Laser induced damage is frequently a problem of defects in optical thin films$^{1-7}$. These defects could be introduced into the films from the preparation process including polishing and cleaning or coating deposition and their forms could be cracks, pores, and absorbing inclusions. Abundant of theoretical and experimental studies have shown that the defects are not easy to identify and characterize because they have nano-scale size and they can’t be observed directly$^{8-12}$. Therefore a lot of effort has been made recently to develop tools and methods for studying the defects characteristics for understanding the laser induced mechanism and feedback on manufacturing process.

An approach proved to be of great interest for studying defect information in optical thin films is plotting laser induced damage probability curves. Several models have been developed. A two-parameter damage probability law and a three-parameter damage probability law have been imposed to investigate the defect damage threshold and the defect densities. Both these laws can often give better fits of measurement curves$^{13-17}$. Another approach is to utilize spot size effect on laser induced damage to optical thin films. This approach relies on statistical tests made at different fluences on the sample, with a given spot size diameter. Capoulade et al.$^{13}$ and Krol et al.$^{14}$ have demonstrated this approach in detail and given a satisfying result. Unfortunately, several unknown parameters such as defect damage threshold and defect density can be involved, so these methods are not easy to reveal the defect information.

For the work presented in this paper, we will present a theoretical method for the retrieval of defect density in point of view of spot size dependence of laser induced damage probability, which avoids the defect damage threshold that cannot be measured directly.

2 General Formula

According to Foltyn$^{16}$, the damage probability can be written as:

$$P_0 = 1 - \left( \frac{F_{th}}{F_0} \right)^{\frac{\omega_0 d_0}{2}} \quad \ldots (1)$$

where $F_{th}$ is the damage threshold of defect, $F_0$ is the peak fluence of irradiated Gaussian laser beam, $\omega_0$ is the spot size diameters of the laser beam, $d_0$ is the defect density, and $P_0$ is the corresponding damage probability. Conventionally, the damage probability is treated as function of irradiated laser fluence $F_0$ with a settled spot size, and the characteristics of defect can be obtained from fitting the damage probability through 0 to 100%. However, according to Eq. (1), damage probability can also be treated as a function of the spot size diameters under some settled fluence...
of the irradiated laser beam. Then, we introduce a new parameter \( r(F_0) \), that is the differential coefficient of the damage probabilities with respect to the spot size, which is given by:

\[
r(F_0) = \frac{\partial P_d}{\partial \omega_0} = -\pi \omega_0 d_0 \left( \frac{F_{th}}{F_0} \right)^{\frac{m_{th} \omega_0}{2}} \ln \left( \frac{F_{th}}{F_0} \right) \quad \ldots (2)
\]

If the optical thin film is irradiated by two different laser fluences which are \( F_1 \) and \( F_2 \), the corresponding parameters \( r \) can be written as follows:

\[
r(F_1) = -\pi \omega_0 d_0 \left( \frac{F_{th}}{F_1} \right)^{\frac{m_{th} \omega_0}{2}} \ln \left( \frac{F_{th}}{F_1} \right) \quad \ldots (3)
\]

\[
r(F_2) = -\pi \omega_0 d_0 \left( \frac{F_{th}}{F_2} \right)^{\frac{m_{th} \omega_0}{2}} \ln \left( \frac{F_{th}}{F_2} \right) \quad \ldots (4)
\]

By dividing Eq. (4) by Eq. (3), and considering in physics, we can assume that \( F_1 \ll F_2 \) and \( F_{th} \ll F_2 \), then we have:

\[
\ln \left( \frac{r(F_2)}{r(F_1)} \right) = \left( \frac{\pi \omega_0^2 d_0}{2} - 1 \right) \ln \left( \frac{F_1}{F_2} \right) \quad \ldots (5)
\]

Then the defect density \( d_0 \) can be derived from Eq. (5):

\[
d_0 = \frac{2}{\pi \omega_0^2} \left[ 1 + \frac{\ln \left( \frac{r(F_2)}{r(F_1)} \right)}{\ln \left( \frac{F_1}{F_2} \right)} \right] \quad \ldots (6)
\]

From this equation, we see that the defect density \( d_0 \) can be conveniently calculated from the diameter of the spot size, the irradiated laser fluence and the differential coefficient of the damage probabilities with respect to the spot size. All these parameters can be obtained easily from experiments directly. Meanwhile, the defect damage threshold that can’t be measured directly is avoided, which is the greatest advantage than the former mentioned approaches.

### 3 Simulation and Discussion

In order to calculate the defect density, firstly, we plot the damage probability curves (Fig. 1) theoretically from Eq. (1). For convenience, the parameters \( F_0 \) and \( F_{th} \) can be considered as one in the form \( F_0/F_{th} \) which is taken as 1.2, 1.5, 2.0, 2.5, 3.0 and 3.5, respectively. At the same time, the value of defect density is set to be \( 5 \times 10^3 \text{cm}^{-2} \). In Fig. 1, each curve shows the relation between damage probability and spot size at the corresponding \( F_0/F_{th} \). Then, the differential coefficients of the damage probabilities with respect to the spot size \( r(F_0) \) for the corresponding curves in Fig. 1 are presented respectively in Fig. 2. Theoretically, all the parameters \( r(F_0) \) could be used to calculate the defect density. However, it is found that the parameters \( r(F_0) \) on the left side of line 1 and the right side of line 2 in Fig. 2 are not suitable for calculating the defect density. The calculated defect densities are negative for the former ones. This may be caused by the fact that the number of the defects included in the spot is too small to present the actual information of the
The parameters \( r(F_0) \) on the right side of line 2 are also not optimum for calculating the defect density because all the values are approaching zero, which are difficult to observe in practice. Therefore, the parameters \( r(F_0) \) between line 1 and line 2 are recommended to be adopted to calculate the defect density. Then, according to Eq. (6) and Fig. 2, the simulated results of damage defect densities \( d_0 \) are shown in Fig. 3 with the spot size diameter of 300 \( \mu \)m which is between line 1 and line 2. In Fig. 3, the parameters of \( F_2/F_1 \) are taken as the ratios 1.2/3.5, 1.5/3.5, 2.0/3.5, 2.5/3.5 and 3.0/3.5. From Fig. 3, we can see that the calculated defect density agrees well with the set density value (5\( \times \)10\(^3\)/cm\(^2\)). The results indicate that this method can be used to analyze the defect information conveniently.

In the above simulation process, the defect damage threshold \( F_{th} \) was used to get the theoretical damage probability curves in Fig. 1. However, we can get the damage probability curve from the experiment directly without the \( F_{th} \). In the application of the proposed method to obtain the defect density, the precision of damage probability affects the calculated results directly. If the precision of damage probability test is improved, the calculated results of defect density with the experiment damage probability curves will be enhanced.

4 Conclusions

In summary, a new method to obtain defect density in optical thin film was presented. It was demonstrated by theory that the defect density can be calculated efficiently from the differential coefficient of the damage probabilities with respect to the spot size. The distinctive advantage of this method lies in the avoidance of the value of the defect damage threshold which can not be measured directly. The calculated defect density agrees well with the set density value. The retrieval method presented here may have potential applications in analyzing the role of defect in the process of laser damage and laser conditioning of the optical thin film.

Acknowledgement

This work was supported by the Research Foundation for Youth Scholars of Beijing Technology and Business University (Grant Nos. QNJ2014-19 and QNJ2017-01), the National Natural Science Foundation of China (Grant Nos. 11575015 and 61705003), and Scientific Research Common Program of Beijing Municipal Commission of Education (Grant No. SQKM20170011009).

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