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Investigation of nanoprecursors threshold distribution in laser-damage testing

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Abstract

A statistical model of nanoprecursors threshold distribution for the interpretation of laser-damage probability curves is investigated. Each kind of precursor is characterized by a Gaussian distribution of threshold. Accurate probability curves of laser-induced damage (1-on-1, 5-ns single shot at 1.064-μm) are plotted in the bulk and at the surfaces of optical components. Results are then fitted with the model presented. A good agreement is obtained between theory and experiment, which permits to identify different kinds of defects and extract their densities and threshold distribution. The interpretation of these data is then discussed according to their nature and origin (cleaning and polishing).

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1. Introduction

Laser-induced damage in optical components is often a problem of defects, located on surfaces and interfaces or in the bulk of coatings and substrates. Different theoretical and experimental studies have shown that absorbing nanometer-sized particles are responsible for the initiation of the damage process [1–7]. In most cases, they are not identified since they can have nanoscale size and can be distributed at low concentration. One way to obtain information on these defects, also referred as "nanoprecursors", is to plot laser-damage probability curves. Indeed, different models have been developed [8–12], which permit the interpretation

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of laser-damage probability curves and involve parameters such as nanoprecursor threshold and densities.

One of these models [8,11] assumes that all defects of a given class fail at the same laser fluence. It leads to a two-parameter damage probability law that provides the damage threshold and the defect density. In some cases, this simple assumption perfectly fits the measurement curve. Nevertheless in numerous cases, improvements in the metrology of laser damage has highlighted some discrepancies between this theory and experiment. Another model [9,10] assumes that defects cause damage according to a power law and leads to a three-parameter damage probability law. It provides information about the shape of the defect ensemble in addition to the damage threshold and the defect density. This second model can often give better fits of measurement curves.

In this paper, we go further in the investigation by considering a Gaussian distribution of nanoprecursor thresholds. Physically, all defects of a given class cannot fail at the same fluence because of a possible size and absorption distribution. Then we propose to use a Gaussian law. Parameters of this distribution (threshold mean value, threshold standard deviation and precursor defect densities) can then be extracted for each kind of observed precursors.

In the first part of the paper, the Gaussian model of threshold distribution is proposed and applied to surface, bulk and thin-film precursors. In the second part, surfaces of different substrates and single layer coatings are analyzed, threshold distribution of defects that are responsible for damage are extracted from measurement curves and commented. In the third part, we discuss the interest of this new model in the understanding of laser-damage probability curves.

2. Model

2.1. Surface precursors

Consider a collection of isolated surface defects under Gaussian laser beam illumination at normal incidence. Each defect is characterized by its own damage threshold T, i.e. all defects of a given class do not fail at the same fluence. The defect population is then specified by the ensemble function $g(T)$, which gives the number of defects per unit area that damage at fluence between T and $T + \mathrm{d}T$. We propose to consider that the ensemble function $g(T)$ follows a Gaussian law (Fig. 1 and Eq. (1)). Then the ensemble function $g(T)$ depends on three parameters: threshold mean value T_0, threshold standard deviation ΔT (full width at $1/e^2$) and defect density d. The relationship between $g(T)$ and defect density d is obtained from normalization condition (Eq. (2)):

$$g(T) = \frac{2d}{\Delta T\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{T - T_0}{\Delta T/2}\right)^2\right], \tag{1}$$

$$\int_0^{\infty} g(T)\,\mathrm{d}T = d. \tag{2}$$

Consider $\mathrm{d}N$, the number of defects located under the laser spot area $S_T(F)$ and whose threshold is between T and $T + \mathrm{d}T$. The laser spot area $S_T(F)$ is the part of the spot size, where energy density F is greater than the precursor threshold T: $S_T(F) = (\pi w^2/2)(\ln(F/T))$, with w, the laser spot radius on the surface sample at the laser waist

$$\mathrm{d}N = g(T)S_T(F)\,\mathrm{d}T, \tag{3}$$

$N(F)$ is the number of defects, located under the laser spot of fluence F and whose threshold is lower than F

$$N(F) = \int_0^{F} g(T)S_T(F)\,\mathrm{d}T. \tag{4}$$

The probability of damage $P(F)$ is the probability of the presence of a defect that receives more

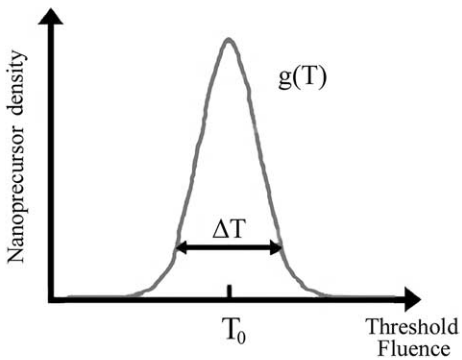

Fig. 1. Gaussian defect distribution.

energy density than its intrinsic threshold. This probability is given by a Poisson law and can be expressed as a function of fluence F or energy per unit of surface:

$$P(F) = 1 - \exp\left(-N(F)\right). \tag{5}$$

The analytical formula for the probability function can be obtained directly with Eqs. (1), (4) and (5)

$$P(F) = 1 - \exp\left[-\frac{\sqrt{\pi}dw^2}{\Delta T\sqrt{2}} \times \int_0^F \exp\left[-\frac{1}{2}\left(\frac{T-T_0}{\Delta T/2}\right)^2\right]\ln\left(\frac{F}{T}\right)\mathrm{d}T\right]. \tag{6}$$

As shown by Eq. (6), damage probability depends now on four parameters T_0, ΔT, d and the laser-spot diameter w. Numerical calculation of $P(F)$ for different values of T_0, $\Delta\ T$, d and w makes it possible to understand the influence of each parameter on the probability curve. Influences of T_0, d and w are already known [8,10,11] (the higher the density or the spot size, the higher the slope of probability curves). In Fig. 2, we illustrate the influence of threshold standard deviation ΔT on the probability curve. We notice that ΔT has an influence on the curvature of the low part of the curve.

The absolute threshold is the greatest value of F that do not lead to a damage, i.e. $P(F) = 0$. However, $P(F)$ is mathematically never equal to zero because of the use of a Gaussian law for the description of the threshold distribution. In fact, the study of several probability curves and their associated best-fit curves show that we can define arbitrary the absolute threshold T_a such as $P(T_a) = 0.001$.

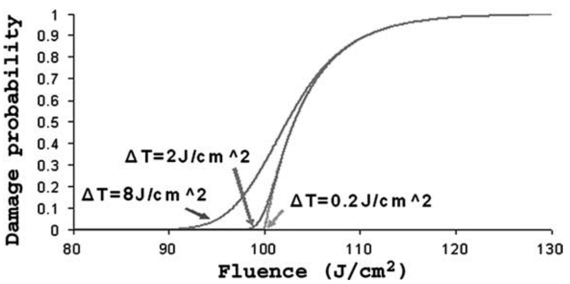

Fig. 2. Influence of threshold standard deviation ΔT on the probability curve. $T_0 = 100$ J/cm^2, $d = 7 \times 10^3$ defects/mm^2 and $w = 6$ μm.

2.2. Bulk precursors

In case of bulk precursors, we have to consider dN, the number of isolated bulk defects located in $V_T(F)$ and whose threshold is between T and $T + \mathrm{d}T$. $V_T(F)$ is the efficient volume, where the energy density F is greater than the precursor threshold (see Fig. 3).

Provided that the beam is Gaussian, the efficient volume $V_T(F)$ is given by Natoli [11]. $N(F)$ can be expressed according to Eq. (4) and then $P(F)$ is obtained with Eq. (5)

$$N(F) = \int_0^F g(T)V_T(F)\,\mathrm{d}T. \tag{7}$$

2.3. Thin-film precursors

The case of thin-film precursors includes the defects found in coating layers but also referred to the defects contained in the polishing layer [4,13–16]. For a layer thickness e, we have to consider

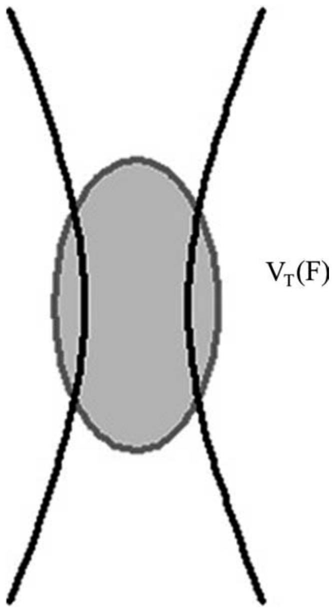

Fig. 3. Laser beam focused in a bulk sample.

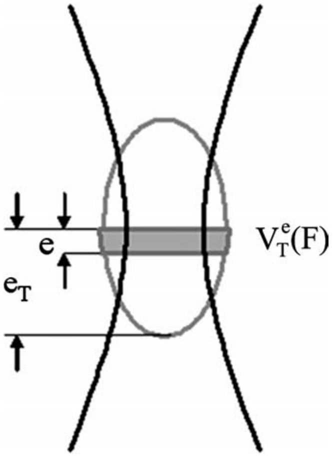

Fig. 4. Laser beam focused on the surface of a thin-film sample.

dN, the number of isolated bulk defects located in $V_T^e(F)$ and whose threshold is between T and $T + \mathrm{d}T$. $V_T^e(F)$ is the efficient volume in the monolayer, where the energy density F is greater than the precursor threshold (see Fig. 4).

The efficient volume $V_T^e(F)$ depends on the thickness e of the monolayer. If $e > e_T = Z_R\sqrt{\frac{F}{T} - 1}$ then $V_T^e(F) = V_T(F)$. If $e < e_T = Z_R\sqrt{\frac{F}{T} - 1}$,

$$V_T^e(F) = \frac{\pi}{2}\int_0^e w^2(z)\ln\left(\frac{F}{T}\frac{w_0^2}{w^2(z)}\right)\mathrm{d}z. \quad (8)$$

If thin-film precursors are uniformly distributed in the efficient volume $V_T^e(F)$ and if $e \ll e_T$, the model with surface precursors can be also applied.

3. Application

The test apparatus [17] involves a single-mode YAG laser beam with 1.064-μm wavelength and 5-ns pulse duration. The damage test procedure 1-on-1 [18] is used. By counting the number of damage regions at each fluence F we estimate the probability curve $P(F)$. To have a good accuracy of the measurement [11], each curve $P(F)$ is plotted with 1000 data points that involve 20 different fluences and 50 tested regions at each fluence, which leads to an absolute accuracy $\Delta P = 0.07$.

The Gaussian model that we have discussed above is applied to the case of substrates and coatings. We estimate the accuracy to ±20% for the defect density d, ±5% for the threshold T_0 and ±10% for the threshold standard deviation ΔT.

Fig. 5 shows the experimental probability curves measured at the front surface of two fused silica substrates. The associated best-fit curves and the defect ensembles extracted from the probability curve are also presented. These two substrates have been polished according to two different processes. We note that the process A leads to an absolute threshold (T_a) of 60 J/cm^2 and to the existence of two classes of defects. The process B leads to an absolute threshold (T_a) of 86 J/cm^2 and to the existence of only one class of defects: equivalent to the second class of defects of process A.

Fig. 6 shows an example of the experimental probability curve measured at the front surface of an Infrasil substrate coated with a Ta_2O_5 single

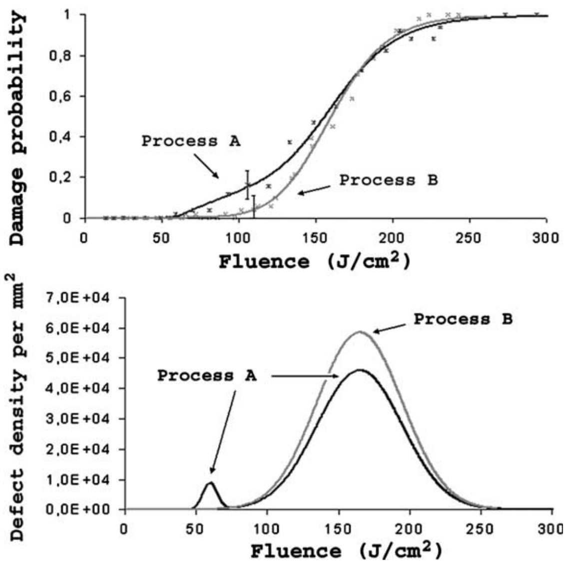

Fig. 5. Probability curves of laser-induced damage measured at the front surface of two fused silica substrates, best-fit curves and Gaussian distribution of precursor thresholds. Process A: two kinds of defects, process B: one kind of defect and improvement of the threshold. Best-fit curves are calculated with the following parameters: $d_1^A = 1.1 \times 10^3$ defects/mm^2, $T_1^A = 60$ J/cm^2, $\Delta T_1^A = 10$ J/cm^2, $d_2^A = 3.4 \times 10^4$ defects/mm^2, $T_2^A = 165$ J/cm^2, $\Delta T_2^A = 60$ J/cm^2, $d^B = 4.4 \times 10^4$ defects/mm^2, $T^B = 165$ J/cm^2, $\Delta T^B = 60$ J/cm^2 and $w = 6$ μm.

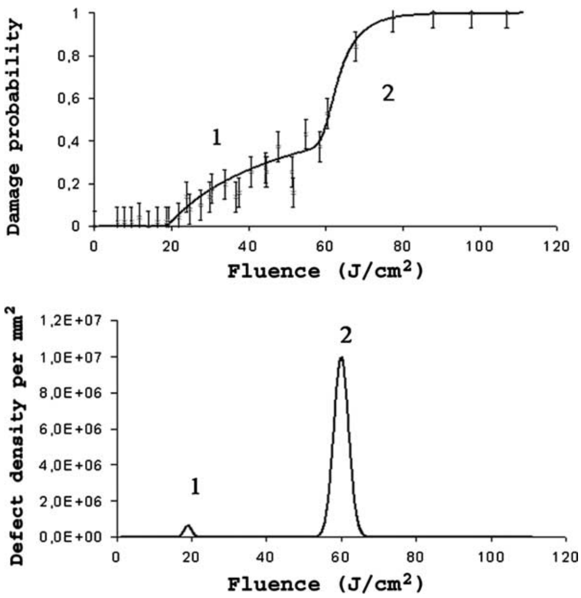

Fig. 6. Probability curves of laser-induced damage measured at the front surface of an Infrasil substrate coated with a Ta_2O_5 single layer (mechanical thickness 1100 nm) deposited by DIBS technique. The best-fit curve and distribution of precursor threshold highlighted two kinds of defects with the following parameters: $d_1 = 16 \times 10^3$ defects/mm^3, $T_1 = 19$ J/cm^2, $\Delta T_1 = 2$ J/cm^2, $d_2 = 5 \times 10^5$ defects/mm^3, $T_2 = 60$ J/cm^2, $\Delta T_2 = 4$ J/cm^2 and $w = 6$ µm.

layer (mechanical thickness 1100 nm) deposited by DIBS technique (Dual Ion Beam Sputtering). The associated best-fit curve and the defect ensemble are also plotted. We note the existence of two classes of defects and an absolute threshold $T_a = 17$ J/cm^2, whereas the absolute threshold of Infrasil substrate without coating is 40 J/cm^2.

This result shows the apparition of defects during the deposition of Ta_2O_5 single layer. These defects can be found in the coating layer but also at the interface between the substrate and the coating. Further studies are needed to understand the role of coating layers and interfaces: influence of mechanical thickness of the single layer and influence of substrate cleaning before deposition.

4. Discussion

The use of a tree-parameter damage probability law (Gaussian model) can often give better fits of measurement curves than a two-parameter law (degenerated model [8,11]). Indeed, in numerous cases, the degenerated model does not fit the measurement curve (Fig. 7). Furthermore, it is not realistic to consider that all defects, precursors of laser-induced damage, have the same damage thresholds. For example, in the case of absorbing precursors, any variation of size, absorption, contact with the host materials can be assumed responsible for variations of damage threshold.

The introduction of a new variable ΔT gives a more precise and realistic information about defects. The results obtained with this refined statistical model could be combined with model predicting the laser-damage initiation threshold [12,19] as a function of inclusion parameters (size and material).

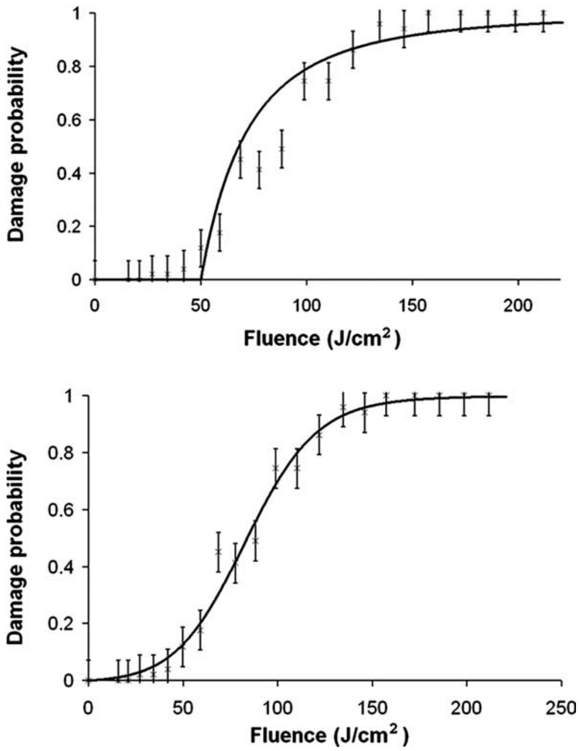

Fig. 7. Probability curve of laser-induced damage measured at the front surface of a BK7 substrate. The curve is fitted with the degenerated model (top) and the Gaussian model (bottom).

5. Conclusion

We have presented a new approach for improving the interpretation of laser-damage probability curves. Indeed laser-induced damage in optical material is often a problem of defects, and our aim was to characterize them as well as possible. Then we have proposed to consider that in a given class of defects, each defect has its own threshold, i.e. thresholds of the defect population are distributed. In this paper, a Gaussian distribution of thresholds has been considered. Other models can be used, but they require a preliminary knowledge of these defects (especially size and absorption). To illustrate our investigation, we have shown experimental results obtained on substrates polished according to different techniques. Results achieved on a Ta_2O_5 single layer are also shown, which establish a good agreement between theory and experiment. This model is of interest for the study of polishing and cleaning processes since it improves the knowledge on laser-damage precursors.

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