

# Measurement of Optical Materials Ablation Threshold Dependence on the Dispersion of Ultrashort Pulses

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**Abstract**—The ablation threshold for ultrashort pulses of common optical materials (BK7 glass, Sapphire and Fused Silica), was measured using the D-Scan technique, for positive and negative dispersions covering pulse durations from 30 fs to 100 fs. We observed that the ablation threshold for a single shot and at saturation increase with the pulse duration and the material bandgap, and also that defects which decrease the threshold values accumulate faster as the material bandgap increases.

**Keywords**—optical materials, ultrashort pulses ablation threshold, incubation effects, D-Scan

## I. INTRODUCTION

The ablation of solid material by ultrashort laser pulses is a consequence of a fast buildup of free electrons by collisional ionizations induced by the laser field that [1, 2], after reaching a critical density around  $10^{21} \text{ cm}^{-3}$ , relax their energy to the ions of the material that are eject from the surface, in a process known as phase explosion. This mechanism is also aided by a Coulomb explosion emerging from the ejection of the electrons from the first nanometers below the surface [3]. The exact contribution of each one of these mechanisms depends on the details of the material and of the laser pulse, but the ablation depends on the presence of free electrons that quiver on the laser electrical field and start the collisional (avalanche) ionization [4, 5]. On metals, these free electrons are already present on the material, and on semiconductors and dielectrics they are created by the pulse leading edge [6, 7].

During the time scale defined by the ultrashort pulses, the interaction of the laser field is predominantly with the electrons, and the ablation threshold of the material (which is the minimum fluence needed for ablation) depends almost exclusively on their presence and the easiness of freeing them.

The presence of defects on the material can increase the density of free electrons on metals, or make their production through laser ionization easier due to the creation of scattering centers or new energy levels in the bandgap [8, 9]. Due to this, the presence of defects usually decreases the material ablation threshold. These defects can be intrinsic to the material, or created by the laser pulse itself [10]; in this case, during a pulsed laser irradiation, subsequent pulses will experiment a lower ablation threshold due to the accumulation of defects originated by individual pulses hitting on the same spot. This ablation threshold modification is a consequence of what are known as incubation effects [11, 12].

To determine the ablation threshold dependence on the pulses superposition in a material and quantify it by an incubation parameter, the ablation threshold must be

measured for many superpositions usually spanning three or four orders of magnitude.

The determination of the ablation threshold is commonly done by the “Zero Damage Method” (ZDM), introduced by Liu in 1982 [13], which requires knowing the laser beam geometry and a precise and stable positioning of the sample on the laser beam focus to know the beam spot size at its surface, and many measurements. This technique can be experimentally demanding for measuring the ablation threshold even for a single shot, and the incubation effects determination requires its repetition for many different pulses superpositions, leading to long laboratory times. Due to these constraints, experimental works usually present results for a small number of superpositions, limiting the comprehension of the defects formation and accumulation mechanisms.

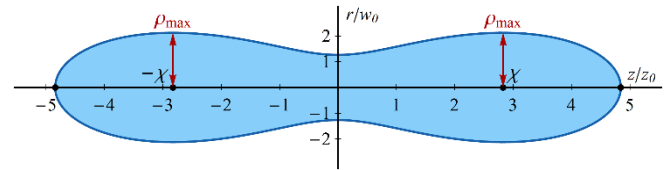


Fig. 1. Profile etched on the sample surface by the D-Scan technique.

A few years ago we introduced the Diagonal Scan (D-Scan) technique [14, 15], a simple procedure to speed up the measurement of the ablation threshold for varying pulses superposition. In this method, the sample under study is diagonally moved across the waist of a focused pulsed laser beam, and a two-lobed profile with maximum width  $2\rho_{\max}$ , like the one shown in Fig. 1, is etched in its surface. It can be shown [14] that the ablation threshold,  $F_{th}$ , is given by:

$$F_{th} = \frac{E_0}{e\pi\rho_{\max}^2} \cong 0.117 \frac{E_0}{\rho_{\max}^2}, \quad (1)$$

where  $E_0$  is the pulse energy. To calculate the pulses superposition  $N$  at the  $\rho_{\max}$  position, it is considered to be the summation of the intensities, at this spot, of each pulse that impinges on the sample, divided by the intensity of the pulse centered at this point; it can be demonstrated that this sum is given by [16]:

$$N = \mathfrak{G}_3(0, \exp\{-[v_y/(f\rho_{\max})]^2\}) \quad (2)$$

where  $\mathfrak{G}_3$  is the Jacobi Theta function of the third kind,  $v_y$  is the sample speed transversally to the laser beam, and  $f$  is the pulses repetition rate.

In dielectrics, the defects can be color centers or any other that create intermediate levels in the bandgap, and their accumulation leads to a model [17] that predicts the existence of a value for single pulses,  $F_{th,1}$ , and a saturation value,  $F_{th,\infty}$ , since there is a maximum defects density. These two values are connected by a transition region characterized by an incubation parameter  $k$ :

$$F_{th,N} = F_{th,\infty} + (F_{th,1} - F_{th,\infty})e^{-k(N-1)}. \quad (3)$$

To determine the ablation parameters  $F_{th,1}$ ,  $F_{th,\infty}$  and  $k$ , of a material, many D-Scan traces covering a variety of superpositions are etched on it, and using (1) and (2), a plot of the ablation threshold dependence on the pulses superposition is done. Fitting (3) to the data provides these ablation parameters.

The ablation threshold, as well as the creation of defects, are the consequences of nonlinear effects, and will depend on the laser pulse intensity. Consequently, their values will depend on the pulses duration [16].

In this work we determined the ablation parameters for three different dielectric optical materials, and studied their dependence on the pulse duration for positive and negative dispersions, to investigate whether the pulse chirp has an effect on their values.

## II. EXPERIMENTAL SETUP

The ablation thresholds were determined for BK7 glass, Sapphire and Fused Silica. These common optical materials are routinely used as windows and as substrates in which microstructures are etched [18, 19], so it is important to know their ablation thresholds to avoid damage in the first case, and to control the inscribing process on the second situation. common optical materials. The measurements were performed in 25 mm diameter, 6 mm thick samples, using ultrashort pulses from a CPA Ti:Sapphire laser system (Femtopower Compact Pro CE-Phase HP/HR, Femtolasers) This system provides pulses centered at 785 nm, in a 4 kHz maximum repetition rate pulse train, with 800  $\mu$ J maximum energy and 25 fs minimum duration (FWHM), in a  $M^2 < 2$  beam. The system has a two pair of prisms compressor, and the pulse duration can be set varying the distance between these pairs of prisms, for either positive or negative dispersions.

The samples were attached to a 3-axis computer-controlled translation stage (3 UTS100CC translators driven by and ESP301 unit, Newport), and the laser beam was focused by a 75 mm focal length achromatic doublet, and all experiments were performed in air with pulses with energy around 90  $\mu$ J. Various combinations of repetition rates and sample transversal displacement speeds were used to cover superpositions from single shot to more than  $10^4$  pulses.

Initially the ultrashort pulses duration dependence on the prisms position was measured to determine which dispersion would be used to allow the measurements in pairs of positive and negative dispersion that would provide similar pulse durations. The pulses durations, temporal and spectral profiles were measured by a FROG device (Frequency Resolved Optical Gating, model 8-20-USB Grenouille, from Swamp Optics).

A pilot experiment was performed to choose the combinations of laser repetition rate and sample transversal

displacement speeds that would cover the desired superposition range.

The D-Scan measurements were done in all three materials for 9 different dispersions, being a null dispersion that generates the shortest possible pulse in our system, with about 30 fs, and 4 positive and 4 negative dispersions covering up to  $\sim 100$  fs. After the D-Scan traces were etched, their dimensions were measured in topographic maps acquired in an optical profilometer (ZeGage, Zygo), and their maximum transversal dimensions,  $2\rho_{max}$  were determined. From these data the  $F_{th}(N)$  curves were plotted using (1) and (2) and the ablation parameters were obtained fitting Eq. (3).

## III. RESULTS

Fig. 2 presents the pulse duration measured by the FROG as a function of the relative micrometer position. At zero position the pulse has 29.1 fs, the shortest possible, and the red points indicate the positions chosen for the measurements: for positive (negative) dispersions the durations are 31.9 (32.3), 55.3 (55.9), 79.8 (83.6) and 98.9 (94.2) fs, forming pairs of similar durations and opposite dispersions.

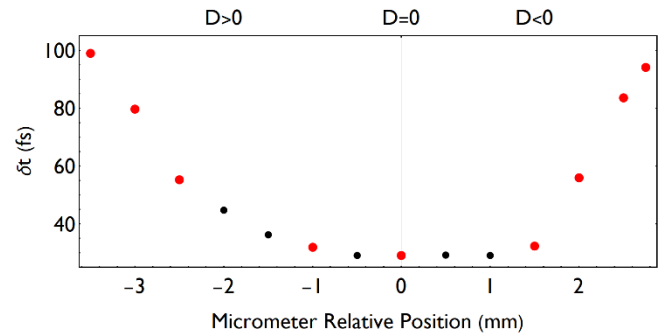


Fig. 2. Pulse duration dependence on the micrometer relative position. The upper scale indicates the signal of the dispersion (D).

Fig. 3 presents the ablation threshold values obtained in the pilot experiment for various combinations of transversal displacement speeds (from 0.02 up to 30 mm/s) and laser repetition rates of 4 kHz, 1 kHz, 500 Hz and 100 Hz. The superpositions  $N$  range from single shot to more than 10,000 pulses and it can be seen that the three higher repetition rates cover this whole range. The data obtained with the lower repetition rate, 100 Hz, provides no additional information, since it covers a subset of the one covered by the 500 Hz measurements. Based on these results, the measurements were done using only the three higher repetition rates (500 Hz, 1 and 4 kHz) and speeds from 0.02 to 30 mm/s.

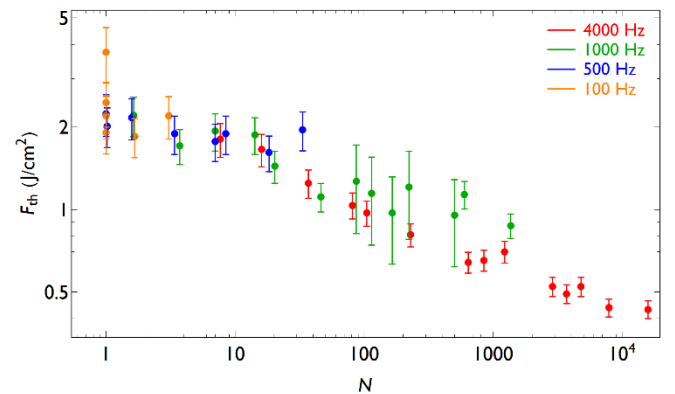


Fig. 3. Pilot experiment ablation threshold results to determine the laser repetition rates and transversal displacement speeds to be used.

Fig. 4 presents the ablation threshold results measured in BK7 glass for 94.2 fs pulses with negative dispersion, along with the fitted curve (red) using the model described by (3). The fitted parameters are shown in the inset providing a single shot ablation threshold  $F_{th,1}=(5.4\pm 0.4)$  J/cm<sup>2</sup>, a saturation ablation threshold  $F_{th,\infty}=(1.98\pm 0.06)$  J/cm<sup>2</sup> and an incubation factor  $k=0.049\pm 0.010$ .

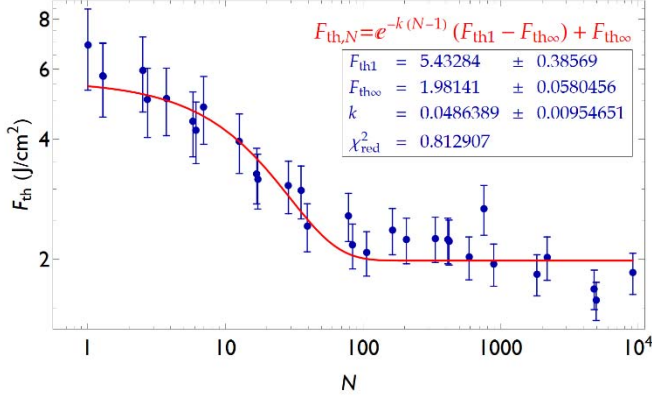


Fig. 4. Ablation threshold dependence on the pulses superposition in BK7 glass for 94.2 fs pulses with negative dispersion.

Similar results were obtained for the other pulse durations, and the BK7 glass ablation parameters dependence on the pulse duration and dispersions are shown on Fig. 5. For the three parameters ( $F_{th,1}$ ,  $F_{th,\infty}$  and  $k$ ) there is a clear trend of increasing values along with the pulse duration. Nevertheless, there seems to be no clear dependence on the dispersion signal: for similar duration pulses the parameter values are very similar (apart from a few points clearly out of the trend). There is no clear behavior of the values being either bigger (or smaller) for positive dispersions when comparing with negative ones. This behavior is similar for the other materials, where the parameters increase with the pulse duration.

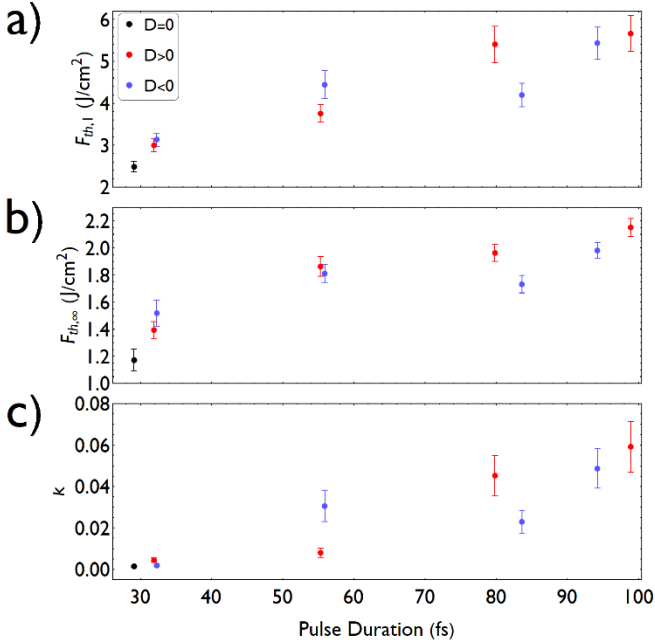


Fig. 5. Ablation parameters for BK7 glass as a function of the pulse duration and dispersion. The black point represents dispersion 0, the red points positive dispersion and blue points negative dispersion. a) Single shot ablation threshold; b) saturation ablation threshold; c) incubation parameter.

Fig. 6 presents the comparative results obtained from the three materials for each ablation parameter. In each graph the parameter growing trend with the pulse duration is observed. Also, in each graph, the BK7 values are always the smallest for a given pulse duration, with the exception of a few points. This behavior can be correlated with the materials' bandgap energy: BK7 has the smaller bandgap, 4.3 eV [20], Sapphire presents an intermediate one, 8.8 eV [21], and Fused Silica has the highest, 9.0 eV [21].

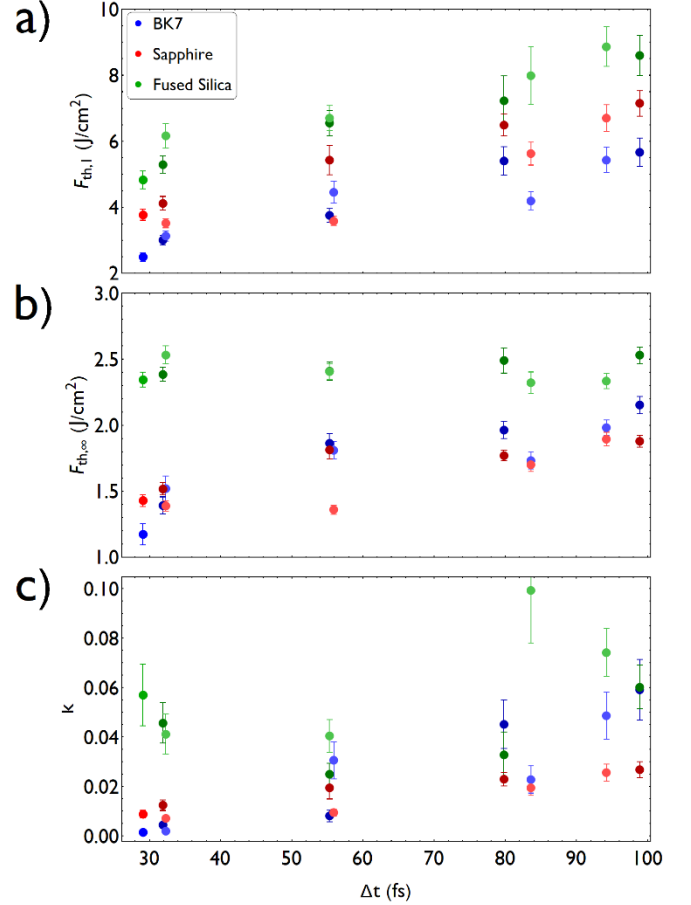


Fig. 6. Ablation Parameters temporal and dispersion dependence for BK7 glass (blue), Sapphire (red) and Fused Silica (green); darker points represent positive dispersion and lighter ones negative dispersion. a) Single shot ablation threshold; b) saturation ablation threshold; c) incubation parameter

#### IV. CONCLUSIONS

Using the D-Scan method we measured the ultrashort pulses ablation threshold for three common dielectric optical materials and determined their dependence on the pulses duration and dispersion. For the precision used in our measurements, there were no observable dependence on the dispersion for pulses with similar durations and opposite signal dispersions. This lack of dependence is presented for the first time to our knowledge. Also, all the ablation parameters get bigger as the material bandgap increases, indicating that material removal (ablation) gets more difficult as the valence electron binding force gets stronger.

This study will be continued to obtain more precise results and to check whether the points that not fit into the trends are due to systematic experimental errors or represent a real material behavior.

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