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# Femtosecond laser ablation of dielectrics: Wavelength scaling from ultraviolet to mid-infrared

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In the frame of femtosecond laser processing of transparent materials, the relative role of the different absorption mechanisms (multiphoton, tunneling and impact ionization) as a function of the pulse duration has been extensively explored. Similarly, as mathematically described by Keldysh formulation, different relative contributions should appear when changing the laser wavelength. However, until present the experimental studies exploring the spectral domain have been rare. Here, we present detailed studies on the single-shot ablation characteristics of dielectrics induced by femtosecond pulses (approx. 200-fs pulse duration) ranging from the ultraviolet to the mid-infrared range.

First, a validated metrology for precise determination of the fluence threshold for surface ablation will be shown. Our method, an extension of the extensively applied  $D^2$ -method, has the advantage to be applicable to imperfect beams profiles [1] and holds whatever the non-linearity of the absorption processes [2]. We will demonstrate that this proposed method gives a robust solution for exact threshold determination without any added technical complications, as for instance advanced control or metrology of the beam profile. Secondly, we explore the evolution of the ablation fluence thresholds (rigorously measured) as a function of the wavelength in dielectrics of reference: fused silica (two kinds), sapphire and soda-lime glass. As shown in Figure 1 (a) for fused silica, but similarly for all the studied materials, an increase up to near infrared followed by a plateau spanning over three octaves up to 3500 nm is observed. Supported by ionization rate calculations, this behaviour can be interpreted by the balance between collision-assisted processes, very efficient on the infrared, and a moderate role of strong-field ionization (mostly via tunnelling) but relevant for ignition of those processes.

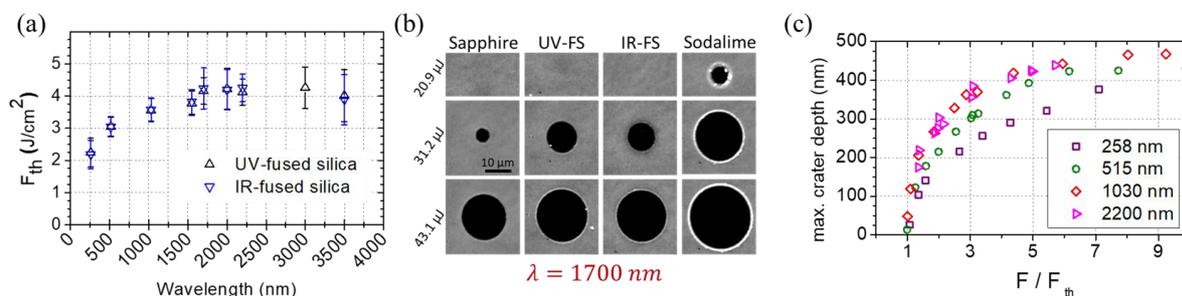


Figure 1 (a) Single pulse ablation fluence threshold on the two kind of fused silica at different irradiation wavelengths. (b) Confocal microscopy images of the craters induced in four different dielectrics with 1700-nm laser pulses (the pulse energy is labelled). Depressions and elevations are represented respectively with darker and clearer colours. Black color corresponds to depressions below 10 nm depth. (c) Maximum crater depth produced in UV-fused silica under a single-shot irradiation at different excitation levels ( $F/F_{th}$ ).

Additionally, a topographic analysis of the induced ablation features is performed. This analysis allows to observe that the quality of the processing (debris ejection and formation of rims) is independent on the laser wavelength and is only affected by the material properties (example for  $\lambda = 1700$  nm is shown in Figure 1 (b)). Also, this study reveals deeper drilling is achieved on the infrared range (Figure 1 (c)). At high fluences, a similar crater saturation depth is found for all tested wavelengths. A major conclusion for technological consideration is the very modest variance of all ablation characteristics in the broad spectral window investigated validating the relevance of new emerging sources for precision machining applications [3].

[1] M. Garcia-Lechuga, and D. Grojo "Simple and robust method for determination of laser fluence thresholds for material modifications: an extension of Liu's approach to imperfect beams " Open Research Europe (in press).

[2] M. Garcia-Lechuga, O. Utéza, N. Sanner, and D. Grojo, "Evidencing the nonlinearity independence of resolution in femtosecond laser ablation," Opt. Lett. 45, 952 (2020).

[3] M. Garcia-Lechuga, O. Utéza, N. Sanner, and D. Grojo, "Near-invariance of femtosecond laser dielectric ablation spanning over three octaves" (to be published)