Manx Precision Optics Ltd. - Technical Note 2016-01

Manx Precision Optic

TN2016-01: Laser-induced Damage Threshold in the ultrashort Pulse Regime

Over the last several years much research has taken place to better understand the mechanisms that govern the laser-induced damage threshold (LIDT) in the ultrashort pulse regime.

For pulses with a duration of 0.5ns and above, the LIDT mechanisms and the scaling of LIDT from a given pulse duration to another one are well understood for practical purposes. However, the development of more and more powerful laser sources for ultrashort pulses and the tendency to generate shorter and shorter pulses has made it more difficult to fully understand the LIDT and related scaling factors in this pulse duration regime.

This technical is looking at the current state of research. When moving to sub-ns pulses the 'traditional' scaling law where the LIDT scales with the square root of the pulse duration becomes more and more unreliable. Furthermore, while metal coatings traditionally show a relatively low LIDT in the ns pulse regime, this changes when moving to pulse durations in the fs regime.

In all cases, laser induced damage is a result of energy transfer between the laser pulse and the material. The ultimate damage depends very much on the type of material (dielectric or metal) and the duration of the pulse. Investigation of fs-pulses appears to the much more predictable than damage related to ps- or ns-pulses [JOG2003]. Where the pulses are longer it is often the case that the damage is the result of absorption by small, randomly distributed defects. When moving to shorter (fs) pulses, we are dealing with much higher intensities that can lead to multiphoton ionisation. In the fs pulse regime this is the dominating factor with regards to laser-induces damage.

Lenzner et al. [LEN1998] have shown that LIDT tests with fs-pulses give very predictable results in 1-on-1 testing. Much work was done by Mero et al. [MER2004 and MER2005] to establish an (empirical) formula to predict the LIDT of commonly used coating materials in the fs-regime. The suggested scaling is as follows:

$$F_{th} \approx (c_1 + c_2 E_g) \tau^{\kappa}_p$$

F_{th}: critical fluence
E_g: material band gap
τ_p: pulse duration
κ: material specific constant
c_1: empirical factor, -0.16+/-0.02 $J/cm^2 fs^k$
c_2: empirical factor, 0.074+/-0.004 $J/cm^2 fs^k eV^k$

The factors c_1 and c_2 are empirical and only show a very weak dependance on film deposition and post deposition treatment. Having been determined from work based on oxide materials it is likely that they will change with other types of coating materials.

For commonly used coating materials, Mero et.al. give the material specific constants and electron band gaps. When inserted into the above formula, they suggest values for the critical fluence as per the table below:

Material	n_{800} (refractive index at 800nm)	E_0 (band gap energy)	k	Theoretical critical fluence in J/cm^2 at 15fs
TiO2	2.39	3.3eV	0.28+/-0.02	0.18
Ta2O5	2.17	3.8eV	0.33+/-0.02	0.30
HfO2	2.09	5.1eV	0.30+/-0.01	0.49
Al2O3	1.65	6.5eV	0.27+/-0.01	0.67
SiO2	1.5	8.3eV	0.33+/-0.01	1.11

More recent work by Mangote et al [MAN2012] investigated the relationship between the material's refractive idex and the LIDT. This work was undertaken at 1030nm and using a pulse duration of 500fs. The empirical law that was found is

$$\mathrm{LIDT} = 12/n^2 \ \mathrm{J/cm^2}$$

When moving from 1-on-1 tests to s-on-1 tests, which are more realistic in day-to-day life, the measured LIDT will reduce. However, more work needs to be done to fully understand the theoretical background of the empirical formulae found.

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