UltraFast Innovations

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Application note:

Laser Induced Damage Threshold of ultrafast dispersive optics

Whether it is to form an optical cavity, to control dispersion, or merely to transport the laser beam, multilayer mirrors are fundamental components of every ultrafast laser system.

Aside from generating ever shorter pulses, ultrafast optics strives to achieve ever higher pulse energies and/or output power. In addition to the well-established state-of-the-art high energy Ti:Sapphire ultrafast systems driving experiments of high field and attosecond science, the past two decades have seen rapid development of oscillators and amplifiers, based on fiber, innoslab, and thin-disk technology. Operating at a central wavelength of and around 1030 nm, these systems are capable of generating sub-picosecond pulses with energies of several tens of μJ at repetition rates of more than 10 MHz, resulting in several hundreds of watts of average output power and multiple megawatts of peak power. Moreover, their output is often intensified further in regenerative amplifiers, optical parametric amplification (OPA) stages, and inside enhancement cavities. The latter can reach average intracavity power of several tens of kW.

Meanwhile, laser induced damage threshold (LIDT) of optical components, in general, and of multilayer thin film coatings, in particular, remains to be among the challenges towards further advances of these technologies.

The history of research on laser-induced damage is almost as old as the history of the laser itself. The optical breakdown induced by nanosecond pulses has been the subject of extensive research over many years and is still investigated today because of the great variety of industrial applications of nanosecond lasers. Similarly, the advance of ultrafast lasers has motivated considerable research on ultra-short pulse optical breakdown of both thin-films and bulk dielectrics.

Mechanisms of LIDT in ultrafast regime:

Unlike in the nanosecond regime, the optical breakdown of dielectrics in the ultrashort regime is driven by fundamental physical processes.

It begins with promotion of valence electrons to the conduction band. When the density of free carriers reaches some critical value, the incident laser field starts to absorb strongly, leading to ablation. Here the damage appears.

Mainly two mechanisms contribute to the promotion of free carriers to the conduction band: photoionization and impact ionization. The first occurs when a valence electron is excited under the influence of the external field whether via multiphoton ionization or via tunneling ionization. The impact ionization takes place when an energetic electron in the conduction band interacts with a valence band electron giving it enough energy to reach the conduction band, resulting in two conduction band electrons. This is also known as avalanche ionization.

Therefore, the laser-induced damage overall, and in ultrashort regime especially, is a sophisticated phenomenon. It depends not only on the properties of the material, such as the band gap, but also on various parameters of the beam: pulse duration, central wavelength, number of pulses, repetition rate, etc.

LIDT @800 nm [1]

Test conditions:

System: Ti:Sapphire, 30 fs pulse @ central wavelength of 790 nm, @ repetition rate of 500 Hz. Up to 1mJ pulse energy [2]. Focal spot on the sample ~Ø140 μm @ 1/e2. Maximal fluence on the sample: 13 J/cm2.

Samples and results:

All the sample designs were coated on fused silica substrates with Ø1" x 0.25" thk. The metal coatings were deposited using electron beam evaporation (EB), whereas the dielectric coatings were produced using plasma-ion assisted magnetron sputtering (MS). E_g – bandgap energy.

	Material	Deposition method	LIDT (J/cm²)
Single layers:			
Ta_2O_5 (E_g = 3.8 eV)	-	MS	0.31±0.03
Nb_2O_5 (E_g = 3.4 eV)	-	MS	0.23±0.03
SiO_2 (E_g = 8.3 eV)	-	MS	1.14±0.03
Metal coatings:			
Protected silver	Ag + Al_2O_3	EB	0.25±0.03
Gold	Au	EB	0.22±0.03
High reflectors:			
HDT2	Ta_2O_5 / SiO_2	MS	0.25±0.03
Dispersive mirrors:			
PC49*	Nb_2O_5 / SiO_2	MS	0.25±0.03
RHD5**	Ta_2O_5 / SiO_2	MS	0.25±0.03

**PC49 – double-angle mirror pair: R(5° (19°)AOI, 450nm – 970nm, p-pol)› %, GDD(5° (19°)AOI, 450nm – 970nm, p-pol) -40fs²*
***RHD5 – highly dispersive mirror: R(5°AOI, 730nm – 840nm, p-pol)› %, GDD(5°AOI, 730nm – 840nm, p-pol) -500fs²*

Table 1. LIDT of various ultrafast mirrors and single layers at a central wavelength of 800nm.

As can be concluded from the table, in the ultrafast regime @800 nm central wavelength: i.) the damage threshold of the dispersive coatings is close to that of a single layer of the respective high refractive index material used, ii.) the produced high reflectors have damage thresholds close to that of the respective high-index materials which are used for their production, iii.) the damage threshold of metallic mirrors is comparable to the damage threshold of dielectric mirrors.

As both, dispersive coatings and QWOT stacks, have LIDT close to the LIDT of a single layer of the used high-index material and the LIDT of the latter is directly proportional to the band gap of the single layer, in order to increase the LIDT of the coating, one has to choose materials with broad band gaps. However, materials with broader band gaps have lower refractive indices and the usage of such materials in a thin-film coating results in lower refractive index contrast and therefore in lesser achievable combination of bandwidth, reflectance and dispersion. A compromise must be sough.

- 🟥 **LIDT mechanisms in the ultrafast regime are different to those in the nanosecond regime**
- 🟧 **LIDT in the ultrafast regime is strongly dependent on central wavelength, pulse duration, repetition rate, etc.**
- 🟧 **LIDT is linearly proportional to the band gap energy of the used high index material**
- 🟨 **Warrantied LIDT of dispersive multilayer mirrors @ central wavelength of 800nm is 0,2 J/cm²**

References:

The note is largely based on Ph.D. Thesis of Ivan B. Angelov "Development of high-damage threshold dispersive coatings", Ludwig-Maximilians-Universität München (2014).

[1] I. B. Angelov, A. Conta, S. A. Trushin, Z. Major, S. Karsch, F. Krausz, V. Pervak. Investigation of the laser-induced damage of dispersive coatings. In Proceedings of SPIE, Vol. 8190, 81900B (2011). Edited by G. J. Exarhos, V. E. Gruzdev, J. A. Menapace, D. Ristau, and M. J. Soileau
[2] I. Ahmad, S. A. Trushin, Z. Major, C. Wandt, S. Klingebiel, T.-J. Wang, V. Pervak, A. Popp, M. Siebold, F. Krausz, S. Karsch. Frontend light source for short-pulse pumped OPCPA system. Applied Physics B **97***, 529–536 (2009).*