Investigation of the laser-induced damage in dispersive coatings

Ivan B. Angelov[a,*], Aaron von Conta[b,c†], Sergei A. Trushin[a], Zsuzsanna Major[a,b], Stefan Karsch[a,b], Ferenc Krausz[a,b] and Vladimir Pervak[b]

[a]Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, D-85748 Garching, Germany
[b]Ludwig-Maximilians-Universität München, Am Coulombwall 1, D-85748 Garching, Germany
[c]Hochschule München, Lothstr. 34, D-80335 München, Germany

ABSTRACT

Different dispersive coatings were tested in terms of laser-induced damage threshold by using a Ti:Sapphire laser yielding 1 mJ, 30 fs pulses at 500 Hz repetition rate at 790 nm central wavelength. The beam was focused down to 140 μm. Single layer coatings of Au, Ag, Nb_2O_5, SiO_2, Ta_2O_5 and mixtures of Ta_2O_5 and silica were examined as well as different dispersive coatings. We observed a direct dependence of the damage threshold on the band gap of the materials used to produce the different samples. The damage threshold values for the dispersive coatings employing the same high index material lay within a range of 30% of each other.

Keywords: LIDT, thin-films, dispersive coatings, oxide mixtures

1. INTRODUCTION

Ultrafast lasers pave the way for the observation of electron dynamics in molecules and atoms in real time,[1,2] as well as high resolution spectroscopy.[3,4] The invention of dispersive mirrors[5] and later their consequent improvement[6–9] boosted the development of ultrafast lasers by providing an easier way to control the amplitude and the spectral phase of the pulse.[10]

However, the generation of ultrashort pulses with large pulse energies is constrained by the laser-induced damage threshold (LIDT) of the optics involved. In particular, the LIDT of the dispersive optics is arguably one of the weakest points in the development of high-power ultrafast systems.

The processes governing the damage in optical materials, induced by ultrashort laser pulses have been extensively studied over the years.[11–17] In this paper we present an investigation on the breakdown thresholds of single layer coatings of metals (Au, Ag), metal oxides (Nb_2O_5, Ta_2O_5, SiO_2), mixtures of Ta_2O_5 with SiO_2 in two different ratios, quarter wave optical thickness (QWOT) stacks, and a number of multilayer dispersive coatings. The samples are described in more detail in Section 3.

2. EXPERIMENTAL SETUP

For our measurements we used the frontend light source for the Petawatt Field Synthesizer (PFS) system which is currently under development in our group at the Max Planck Institute of Quantum Optics.[18] For the current experiment it delivered pulses with energy of 1 mJ and duration of about 30 fs at a central wavelength of 790 nm with a repetition rate of 500 Hz.

We utilized a rapid change of the scattering behaviour of the sample as an indicator for damage. Such method for damage detection has been used previously in experiments by other groups.[19,20] It is also recommended by ISO 11254-2, which specifies the determination of multiple pulse laser-induced damage threshold of optical surfaces.

The layout of our experimental setup is given in Figure 1. The beam first went through a motorized filter wheel with an azimuthal gradient distribution of the optical density. By rotating the filter wheel we were able to control the illuminating fluence on the sample. After passing the neutral density filter, a small part of the beam

* E-mail: ivan.angelov@mpq.mpg.de; Tel.: +49 89 289 14095; Fax: +49 89 289 14141; http://www.attoworld.de/
† Current address: Lund University, Professorsgatan 1, SWE-22363 Lund, Sweden

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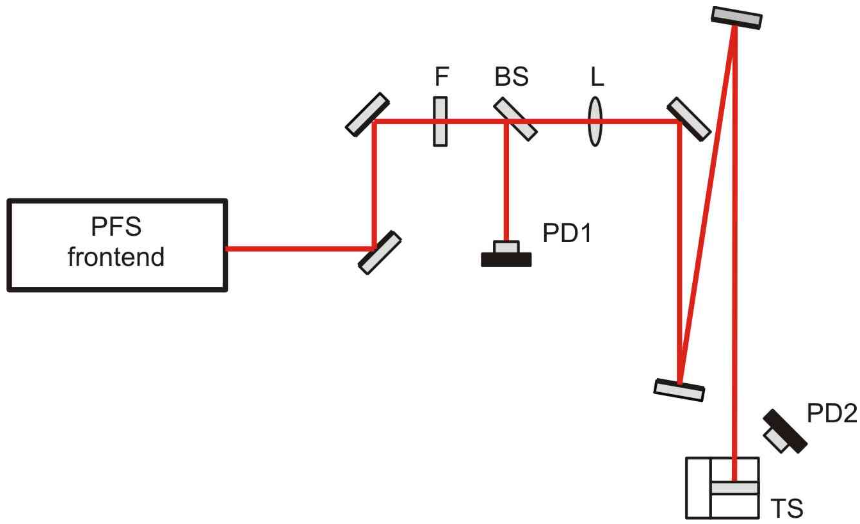


Figure 1: Layout of the setup: F – gradient neutral density filter wheel; BS – beam splitter; L – 1500 mm convex lens; PD1 – calibrated photo diode; PD2 – photo diode to detect scattered light; TS – 3D translation stage.

was reflected by the beam splitter. It was then sent to a calibrated photo diode, which allowed us to measure *in situ* the incident power. The rest of the beam was focused on the sample down to a spot with diameter of about 140 μm measured at level $1/e^2$ of the maximal intensity. A second photo diode was placed near the sample in order to detect any scattered light from the surface of the sample.

By having a maximal pulse energy of 1 mJ, we were able to achieve fluences of up to 13 J/cm^2.

We used the following measurement procedure. The sample was placed in such a way that an undamaged site of the sample was positioned in the focus of the laser beam. The scattered light was then measured for a certain period of time (typically 10 s). Then the fluence was increased and the scattered light was measured again for the same time interval, while illuminating the sample on the same spot. That procedure was repeated until eventually scattered light increased rapidly, which indicated damage.

Note that ISO11254-2 requires the beam to be moved to a new spot on the sample for each fluence level to which it is being exposed. That has been done in order to avoid previously reported incubation effects.[13,16,21–23] Since such preconditioning effects are part of the long term damage process, we consider that by embracing these incubation effects our measurements actually yielded more realistic threshold values for the damage, which occurs under real conditions.

3. SAMPLE DESCRIPTION

In this study we investigated high-reflectors, dispersive mirrors, a fused silica substrate and single layer coatings of metal and dielectric materials. All of the sample designs were coated on fused silica substrates with 25 mm diameter and 6 mm thickness. Information about the different coatings is summarised in Table 1. All of the dielectric coatings presented here were produced using plasma-ion assisted magnetron sputtering.

Single layer depositions of Nb_2O_5, Ta_2O_5 and SiO_2 as well as mixtures of the latter two were investigated in terms of LIDT. The mixtures of Ta_2O_5 : SiO_2 had ratios of 80 : 20 and 90 : 10 and are denoted here as Ta_2O_5 80% and Ta_2O_5 90%, respectively.

Both of the metal coatings (Ag and Au) had a physical thickness of about 120 nm and were deposited using electron beam deposition.

For all of the dielectric mirrors SiO_2 was used as the low refractive index material. The samples designed as highly reflecting mirrors, i.e. HDT1 and HDT2, consisted of a QWOT stack with Ta_2O_5 80% and Ta_2O_5 as high index materials, respectively. Each sample among the dispersive mirrors had a unique design in order to meet

Sample name	Materials	Layers	Physical thickness (nm)	Process	Threshold fluence (J/cm^2)
Single layer dielectric coatings:					
Ta_2O_5 (80%)	80% Ta_2O_5 – 20% SiO_2	1	320	MS	0.41 ± 0.06
Ta_2O_5 (90%)	90% Ta_2O_5 – 10% SiO_2	1	300	MS	0.35 ± 0.06
Ta_2O_5	Ta_2O_5	1	300	MS	0.31 ± 0.01
Nb_2O_5	Nb_2O_5	1	300	MS	0.23 ± 0.02
SiO_2	SiO_2	1	400	MS	1.14 ± 0.08
Metal coatings:					
Silver	Ag	1	120	EB	0.25 ± 0.02
Gold	Au	1	120	EB	0.22 ± 0.02
High reflectors:					
HDT1	80% Ta_2O_5/SiO_2	41	5000	MS	0.34 ± 0.04
HDT2	Ta_2O_5/SiO_2	41	4700	MS	0.25 ± 0.04
Dispersive mirrors:					
HD63	Ta_2O_5/SiO_2	63	9680	MS	0.26 ± 0.02
HD64	Ta_2O_5/SiO_2	39	10460	MS	0.35 ± 0.03
HD72	Ta_2O_5/SiO_2	40	10175	MS	0.36 ± 0.01
HD73	Ta_2O_5/SiO_2	71	10990	MS	0.25 ± 0.02
RHD5	Ta_2O_5/SiO_2	67	11300	MS	0.25 ± 0.03
PC49_C	Nb_2O_5/SiO_2	89	8260	MS	0.25 ± 0.02
PC60_S	Nb_2O_5/SiO_2	88	12530	MS	0.29 ± 0.02
PC60_L	Nb_2O_5/SiO_2	84	12140	MS	0.27 ± 0.04

Table 1: General description and breakdown threshold fluences of the studied samples. All of the dielectric samples were prepared using magnetron sputtering (MS); the metal coatings were deposited using electron beam evaporation (EB).

the specific requirements of the experiment for which it was intended. Some of the dispersive coatings employed Ta_2O_5 as high index material, whereas for others Nb_2O_5 was used.

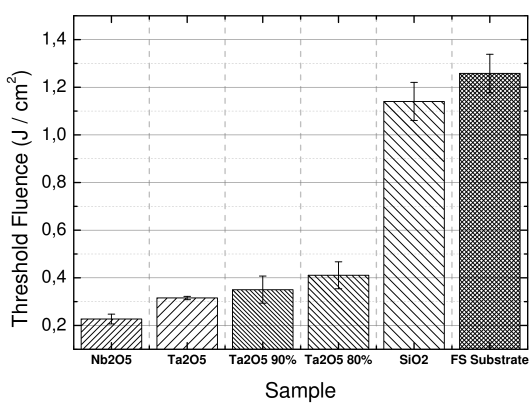
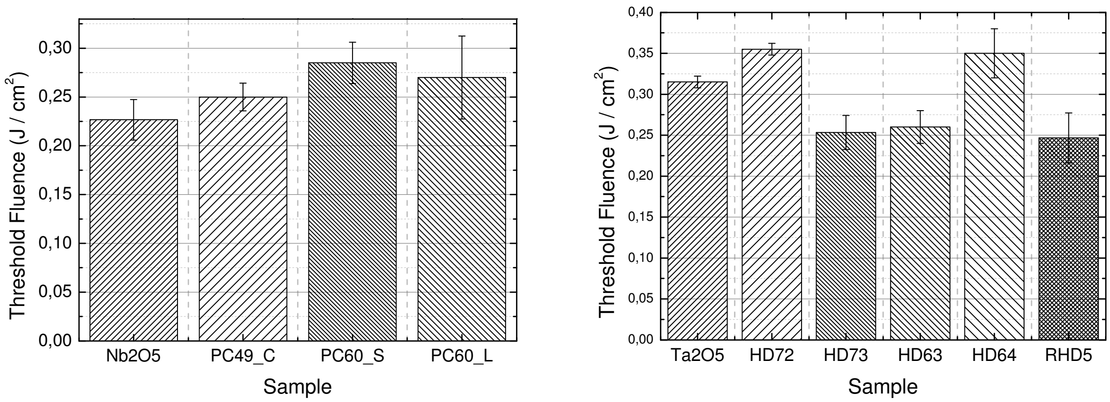


Figure 2: Threshold fluences of single layer deposition and fused silica substrate.

Material	E_g (eV)	n_0
Nb_2O_5	3.4 [24]	2.25
Ta_2O_5	3.8 [15]	2.10
SiO_2	8.3 [15]	1.45

Table 2: Band gap energies (E_g) and refractive indices at 800 nm (n_0) of the investigated materials.



(a) Nb_2O_5 (b) Ta_2O_5

Figure 3: Comparisons between: (a) a single layer of Nb_2O_5 and dispersive coatings employing Nb_2O_5 as high- and SiO_2 as low index materials, respectively; (b) a single layer of Ta_2O_5 and dispersive coatings of Ta_2O_5/SiO_2.

4. RESULTS AND DISCUSSION

The measurements were conducted in different sessions spread across several months. By the date of writing the laser system was still under development and in order to operate properly, adjustments alignment were required on a daily basis. Such realignments led to a slightly different path of the beam in the damage threshold setup, which in turn meant that our setup had to be aligned before each measurement session. All of the above resulted in slightly different calibration parameters and focus position, leading to a systematic day-to-day error of up to 15%.

The optical breakdown thresholds of the single layer depositions are shown on Figure 2. Our measurements confirmed previously reported band gap dependence of the laser-induced damage for ultrashort pulses.[15,20] Also, the values of the threshold fluences for the fused silica substrate and deposited single layer of SiO_2 were close to each other, suggesting good quality of the deposition process.

Figure 3 shows the threshold fluences of two sets of dispersive mirrors and the respective high index material used in each set. Nb_2O_5 was used in the dispersive coatings shown on Figure 3a, whereas Ta_2O_5 was used for the coatings shown on Figure 3b. As can be seen, the damage threshold of the dispersive coatings is close to that of a single layer of the respective high index material used. In the case of Nb_2O_5 the breakdown threshold of the single layer coating was actually a bit lower than that of dispersive mirrors employing that material. One of the reasons for that might be the lower quality substrate used for that particular coating.

On Figure 4 the threshold fluences of two QWOT stacks, i.e. HDT1 and HDT2, are compared with the single layers of the corresponding high index materials (Ta_2O_5 80% and Ta_2O_5). Two observations could be made. First, the produced high reflectors have damage thresholds close to that of the respective high index materials which are used for their production. Second, comparing the threshold fluences of the two QWOT stacks, it can be seen that the one employing the Ta_2O_5 80% mixture as high index material, i.e. HDT1, has about 20% larger damage threshold. Such improvement of the breakdown threshold of a thin-film structure by mixing the high index material with SiO_2 has been reported previously.[25,26] However, due to the fact that the refractive index of the mixture becomes smaller as the concentration of SiO_2 in it increases, this approach can be applied only to a certain extent.

A comparison between the optical breakdown thresholds of metal and dielectric coatings is shown on Figure 5. The small difference between the damage thresholds of both types of coatings was an interesting finding, because previous studies of laser-induced damage for pulse duration in the order of about 0.1 ns show a significantly larger difference between the breakdown thresholds of metals and dielectrics.[27]

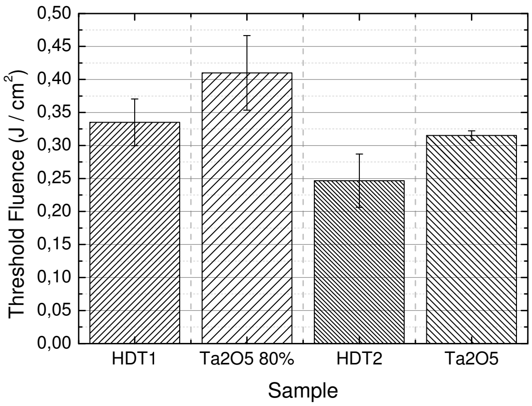


Figure 4: Threshold fluences of QWOTs compared to that of single layer depositions of different high-refractive index materials.

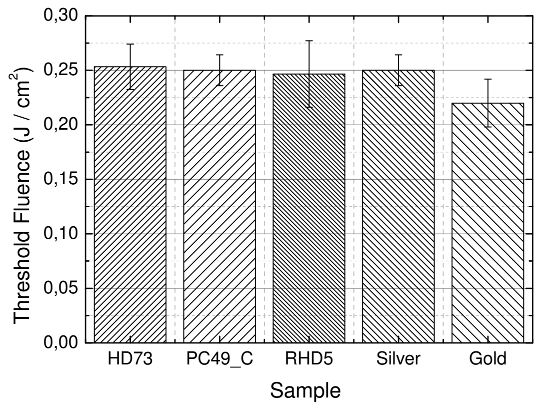


Figure 5: Comparison between the threshold fluences of metal and dielectric mirrors.

5. CONCLUSION

To the best of our knowledge, we are the first to show measurements of LIDT for 30 fs pulses with a spectrum centered around 790 nm and a relatively large spot size of 140 μm. The LIDT of single layer metal and dielectric coatings, QWOT stacks, as well as a number of dispersive coatings were measured and compared.

The damage threshold of the single layer dielectric coatings was found to be dependent on the band gap of the material used. Both QWOT stacks and dispersive coatings had damage thresholds close to that of a single layer of the high index material used for the respective coating. Finally, the difference between the breakdown thresholds of metal mirrors with respect to that of dielectric ones was found to be much smaller compared to previous measurements, conducted with ns pulses.

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Questions and Answers

Q. When you compare the electric field distribution of a quarter wave stack and your dispersive mirror, have you taken into account that the pulse broadens when it enters the mirror when you start with a Fourier limited pulse?

A. That's a very good question. Actually, we didn't take that into account.

Q. So that could be a reason why you are seeing similar damage thresholds because the pulse is just longer.

A. Okay. That might be, but how long can the pulse get in a 10 micrometer stack?

Q. Well, that depends on the resonances and how dispersive your mirror is.

A. Okay. This makes sense. Yes.