Femtosecond damage threshold at kHz and MHz pulse repetition rates

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ABSTRACT

Femtosecond laser-induced damage threshold (LIDT) measurements for different optical components are well studied for a set of laser pulse repetition rates spanning the range between 1 Hz and 1 kHz. Recent years saw the advent of high-repetition-rate femtosecond systems with relatively high pulse energy. Therefore investigation of LIDT in the MHz region is essential. We performed several comparative femtosecond LIDT measurements on typically used ultrafast optical elements with different Ti:Sapphire laser systems having substantially different pulse repetition rates (a 1 kHz regenerative amplifier and a 4.3 MHz long-cavity oscillator) and found a substantially lower MHz LIDT threshhold.

Keywords: laser damage, ultrashort pulses, mirrors.

1. INTRODUCTION

Femtosecond laser induced damage threshold (LIDT) has been studied in many configurations recently. As pulsed lasers with femtosecond pulse length became more available, research of the field has grown fast. There is an ISO standard[1] which describes a measurement procedure. Based on this or other self-consistent methods many groups performed single-shot measurements,[2,3] multi-shot measurements,[4–6] or both.[2,7–9] During multi-shot measurements the repetition rate of the pulses can differ significantly. Many measurements using femtosecond pulses are in the Hz-kHz region[7,10,11] giving a huge amount of data. Without completeness a few of them performed at 800 nm: Chen et al. measured 0.38 J/cm^2 for high reflectors (HR) and 0.08-0.11 J/cm^2 for chirped mirrors.[12] Starke et al. presented results in a round-robin experiment on a HR mirror between 0.2 and 0.7 J/cm^2 depending on number of pulses and experimental facility.[13] Starke et al. also presented LIDT on different type HR mirrors and chirped mirrors with results of 0.2-0.5 J/cm^2 and approximately 0.1 J/cm^2 respectively depending on the sample and number of pulses.[14] LIDT of TiO_2/SiO_2 mirror is also shown, where the results are 0.35-0.5 J/cm^2 depending on the number of TiO_2/SiO_2 layer pairs and the number of pulses.

Further on it is also important to investigate the LIDT with femtosecond pulses at MHz repetition rates. Jasapara et al. reported results with Ta_2O_5/SiO_2 HR mirror between 0.16 and 0.29 J/cm^2, depending on pulse length with 100 MHz repetition rate and very tightly focused (0.60 μm) beam.[15] Also Angelov et al. presented results in the MHz repetition rate region but with picosecond pulses.[16] There are high energy laser systems operating at this repetition rate region. E. g. passively mode-locked Yb thin disc laser[17] with 65 MHz repetition rate, 370 fs pulse width and 20.5 W average power and high power femtosecond fiber chirped-pulse amplification system[18] with 250 MHz repetition rate and 250 W average power.

There are only very few measurements which investigated the LIDT dependence on various repetition rates and these measurements are not matching either. Mero et al. performed measurements on a Ta_2O_5 single layer at 1, 10, 100 and 1000 Hz and did not observe significant changes or any trends in the LIDT.[19] Hertwig et al. achieved similar results on ion-doped glass sample.[20] Contrary to these results Bonse et al. demonstrated a decreasing trend in LIDT values, with measurements taken at 10, 100 and 1000 Hz on a Ta_2O_5/SiO_2 high reflector multilayer.[21] They measured 0.61, 0.45, 0.36 J/cm^2 respectively. One order of magnitude increase in the repetition rate leads to approximately 25% decrease in the LIDT. Due to the sparse literature, it is an important task to investigate the LIDT dependence on the pulse repetition rate especially for higher repetition rates than 1 kHz.

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Therefore we performed several LIDT measurements of mirrors usable in ultrafast laser systems with both kHz and MHz repetition rates at 800 nm wavelength and give a direct comparison, of the femtosecond LIDT values.

2. METHODS

We used two solid state lasers for our measurements. One is a Coherent LEGEND regenerative amplifier and the other is a home built long-cavity Ti:Sapphire oscillator. The parameters of the beams produced by these lasers at the measurement site are summarized in Table 1.

Parameter	Regenerative amplifier	Ti:Sapphire oscillator
Central wavelength (λ)	795 nm	805 nm
Repetition rate	**1 kHz**	**4.3 MHz**
Pulse length, FWHM (τ)	91 fs (35 fs TF)	87-128 fs
Energy stability rms	0.25 %	n/a
Pulse bandwidth, FWHM	30 nm	20 nm
Focused spot size diam.	7.9 μm $\pm$ 0.2 μm	8.2 μm $\pm$ 0.2 μm

Table 1: The parameters of the lasers used for damage testing (TF denotes the Fourier transform limit).

In Fig. 1. a scheme is shown of the measurement setup. The beam is directed to the sample with beam steering mirrors (M) and two pinholes are built in for proper beam alignment. The power is decreased by a wheel absorption filter (WF). A shutter (SH) is built into the beamline to enable S-on-1 measurements. The power reaching the sample was measured with a power meter (P) between the shots. The beam is focused by an f=18 mm (L) lens on the sample which is fixed on an x-y-z translation stage (TS).

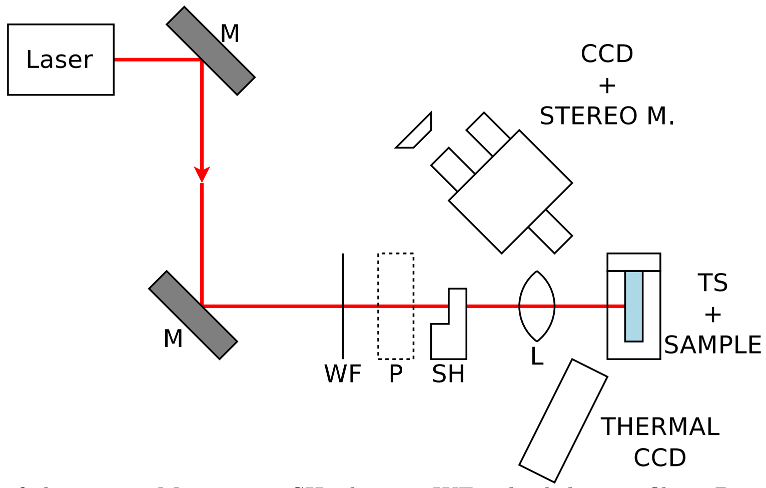


Figure 1: The scheme of the setup. M: mirrors, SH: shutter, WF: wheel density filter, P: power meter, L: f=18 mm achromatic lens, TS: translation stage.

There are two real-time monitoring systems shown in Fig. 1. One shown in the center is a stereo microscope built into the setup. A CCD camera is attached to one of the oculars. The damage is visible with high certainty on the CCD's picture. The other is a thermal CCD with which the heating of the sample can also be visualized.

At the kHz measurements we performed a mixture of the 1-on-1 and the S-on-1 procedures described in the ISO standard.[1] We were able to measure the illumination time but we were unable to stop the beam suddenly at a damage occasion. Therefore our test was using the same number of pulses as in S-on-1 but the probability was only the ratio of the damaged and all sites as in 1-on-1. The damage threshold fluence was defined as the intersection of the linear fit of the data points and the $y = 0$ line as shown in Fig. 2. The error is calculated from the error of the linear regression. We used the shutter to control the beam and the illumination time was 30 s measured by the shutter. This led to 30,000 pulses at 1 kHz.

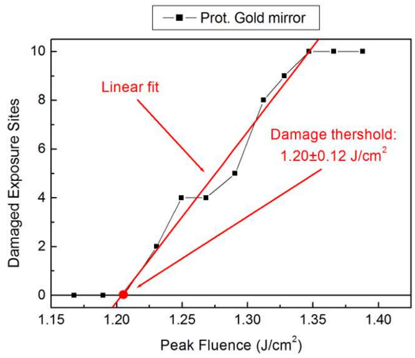


Figure 2: Damage probabilities of protected gold mirror and the determination of damage threshold value from the measurement.

At the MHz measurements we used two methods. (i) We applied approximately 35,000 pulses at 4.3 MHz with a shutter. Further on the LIDT was calculated from five or more illuminated points. We started with an intensity below threshold and increased it at the same irradiated point until we observed the damage. So the LIDT was the mean of the last intensity without damage and the damaging intensity. Then this measurement was repeated at different spots and the final LIDT of the sample was the mean of all former LIDT values denoting to the different points. The error of such a LIDT was given by the standard deviation of the values. (ii) We also performed a measurement similar to the kHz measurements formerly with 30 s irradiation time (108,000,000 pulses) and measured only a little lower LIDT than in the case of method (i).

We give the LIDT in the units of peak fluence that can be given in the form:

$$F = 2\frac{\overline{P}}{f_{rep}}\frac{\cos\theta}{w_0^2\pi}, \tag{1}$$

where $\overline{P}$ is the average power, f_{rep} is the repetition frequency, θ is the beam angle of incidence, w_0 is the beam radius ($1/e^2$ radius, assuming a Gaussian beam).

The pulse energy of the high repetition rate oscillator only allows for damaging at very tight focusing conditions with a 10-micron focal spot. Therefore, to decouple potential effects of the spot size on LIDT, we had to perform similar measurements with the kHz amplifier too.

3. RESULTS

We tested metallic and dielectric mirrors as well as chirped mirrors, representing the most relevant cases for femtosecond technology.. A high reflector mirror centered at 800 nm was manufactured by Optilab Ltd. We will refer to this mirror as HR800 mirror. The high reflector mirror is coated with a dielectric layer structure. The dielectric layer stack is a TiO_2-SiO_2 layer pair repeated 24 times which is a $(LH)^{24}$ stack, where L denotes the SiO_2 (n=1.44) low index and H the TiO_2 (n=2.3) high index layer respectively. We tested protected gold and silver mirrors as well. The protected metal mirrors all have a protecting overcoat which may be, in the most common case, an approximately 100 nm thick SiO_2 layer. Unfortunately the manufacturer does not provide with precise information on the overcoat thickness. Further on we measured a chirped mirror test piece having some manufacturing defects.

The results are summarized in Table 2. In the last column the ratio of the kHz and MHz damage thresholds can be seen. We can observe a factor of 4 to 8 for the dielectric and metallic mirrors, representing a substantial decrease for MHz repetition rates.

Sample	Damage threshold (J/cm^2)		$\frac{\text{LIDT}_{kHz}}{\text{LIDT}_{MHz}}$
	1 kHz	4.3 MHz	
Protected Ag mirror	1.26 ± 0.28	0.166 ± 0.005	7.6
Protected Au mirror	1.20 ± 0.12	0.141 ± 0.010	8.5
HR800 mirror, Optilab Ltd.	0.42 ± 0.09	0.103 ± 0.012	4.1
Chirped mirror	0.16 ± 0.03	0.040 ± 0.003	4.0

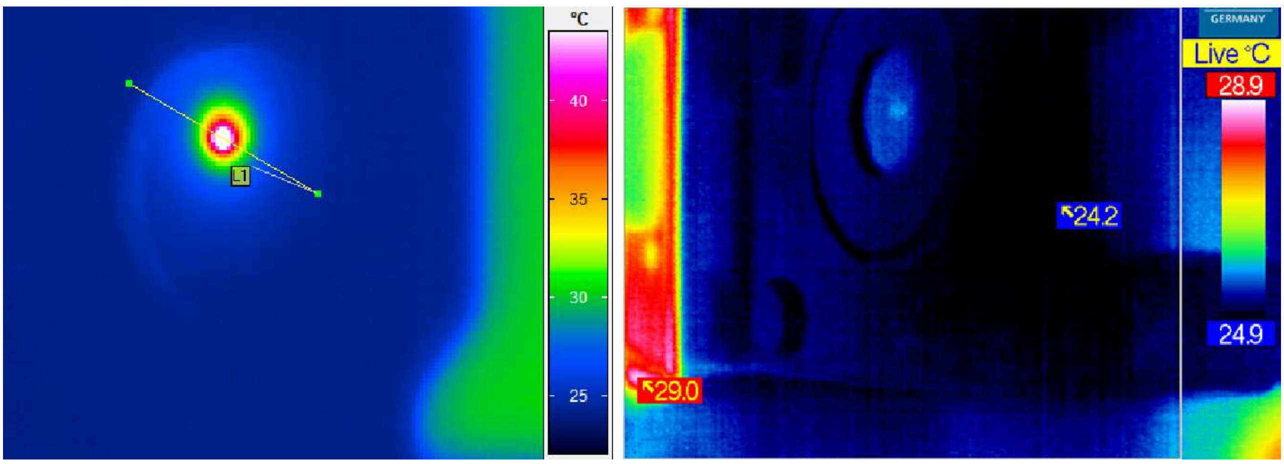
Table 2: LIDT peak fluence the values for the measured samples at the kHz and MHz lasers, and their ratio.

4. DISCUSSION

In all cases measurement inaccuracies of the laser power, the pulse length, the focal spot size (given by the magnification and/or the beam profiler camera evaluation software) are estimated to be less than 1%. The laser instability, caused an error higher than the measurement inaccuracies. These errors were evaluated to account for a total 4-7% error in the measured damage threshold values.

Since the damage fluence depends strongly on whether the beam hits a layer defect or not, the results have high statistical fluctuation. This can be decreased by measuring many samples with the same method or increasing the number of measurement spots of the sample. At the kHz measurement the statistical error can be calculated from the standard error of the slope and the intersection of the linear fit. At the MHz measurement a similar type of error can be calculated as the standard deviation of the values measured at different spots.

We assume that the cause of the remarkable difference between the kHz and MHz damage thresholds is that the damage is assisted by thermal effects. The sample has less time at the MHz measurements to relax so the LIDT decreases with increasing repetition rate. In order to illustrate the thermally assisted femtosecond damage mechanism, we show an alternative diagnostic technique. This is a thermal camera with which the thermally assisted femtosecond damage processes can be investigated. In spite of the fact that heating effects are not expected in the femtosecond region with kHz repetition rate, upon measuring dielectric samples the camera shows heating of the sample. The maximum temperature was nearly 70 degrees Celsius. The camera does not work properly with metal mirrors due to the fact that metal has better heat conductivity and reflects thermal radiation as well. So the heat of the environment is seen by the camera with a very little heating point as shown in Fig. 3(b).The heat camera diagnostics will enable testing damage mechanisms and differences between kHz and MHz repetition rates in the future.



(a) (b)

Figure 3: Thermal camera exposure evaluation on HR800 (a) and Al mirror (b) upon illumination with 35 fs and 1 kHz.

A possible reason for the smaller scaling factor of the dielectric mirrors may be the lower heat conduction. Therefore the heating effects have longer relaxation time in dielectric mirrors than the time between two pulses reach the sample in both kHz and MHz repetition rate cases. In contrary the metallic mirrors have better heat conductivity, which leads to a shorter heating effect relaxation time less or comparable with the time between two pulses at the kHz repetition rate case and much longer relaxation time as the time between two pulses in the MHz repetition rate case.

The origin of such a huge difference between kHz and MHz damage thresholds need to be investigated further on to identify potentially different damage mechanisms (including, for example, thermally assisted femtosecond damage). However these measurements represent a first step to investigate an important new phenomenon. The low damage threshold at high repetition rate has to be taken into account in the construction of some high intensity lasers delivering femtosecond pulses at MHz repetition rates.

5. CONCLUSIONS

The optical damage threshold of mirrors play an important role in laser system manufacturing and development, therefore it is essential to know the LIDT of the elements used. However, in spite of the abundance of nanosecond and picosecond data, less information is available for femtosecond damage threshold, especially for high (100 kHz. . . MHz) repetition rates. For this reason we performed several femtosecond LIDT measurements on typically used ultrafast optical elements.

The kHz results, where comparable, were well matching the earlier ones found in literature. For the first time to our knowledge, we also compared femtosecond damage thresholds with kHz and MHz repetition rates and found a remarkable difference with a factor of 4 to 8 lower values for MHz repetition rates, the origin of which requires further investigation.

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