White Paper

Laser Induced Damage Threshold of Optical Coatings

An IDEX Optics & Photonics White Paper

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INTRODUCTION

Optical components are used in many applications involving the use of high powered lasers. In many cases, the coated surface of the optical component may be exposed to laser power and pulse width conditions that cause the coated surface to reach what is known in the industry as its Laser Induced Damage Threshold (LIDT), or the beam intensity at which damage occurs at the component's surface. LIDT is a function of various parameters including laser wavelength, pulse duration, pulse repetition frequency, spot size, temporal and spatial profile, and angle of incidence. This paper is an introduction and practical guide understanding the nuances of Laser Induced Damage Threshold.

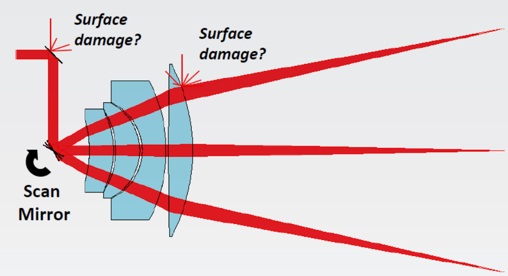

Fig. 1: Illustration of an optical system using a laser light source at levels which may damage the coating on the surface of a lens or mirror within the beam path.

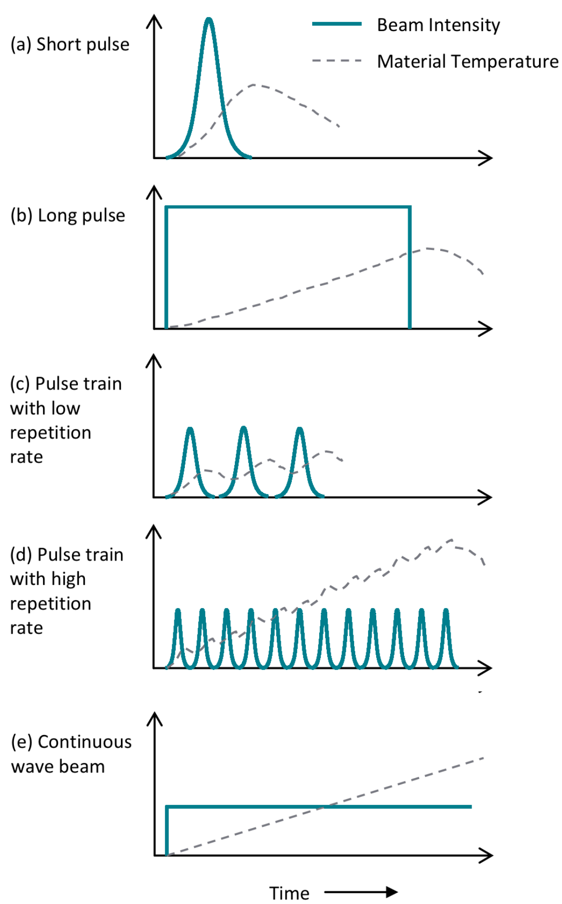

Fig. 2: Illustration of the response of a material's temperature due to absorption of laser beam intensity.

Laser damage mechanisms

What is broadly known about LIDT has been the result of an accumulation of many studies performed by numerous researchers under a variety of test conditions. In fact, according to R. Wood , "There is no one value for the damage threshold for any particular material irrespective of the wavelength, pulse duration, beam size or shape." What has been clear however is that most laser induced damage of optical components may be classified under two primary mechanisms for damage: (a) Dielectric breakdown of the optical material arising from the response of the material's electrons to the incident pulse's electric field density, and (b) Thermal processes resulting from absorption of the laser irradiation by the optical material. Both mechanisms may even occur together under some conditions. The conditions at which the two mechanisms take place are illustrated in Fig. 2.

CVI Laser Optics

In Figs. 2a and 2b, lasers operating with a single short or long pulse may not have a pulse duration long enough for the material to absorb sufficient light energy for its temperature to reach a threshold where thermal processes occur to damage the material. However, if the pulse intensity is high enough, then dielectric breakdown could occur. This situation is similar for pulsed lasers with a very low repetition rate.

In Fig. 2c, if short laser pulses with a somewhat higher repetition rate are repeated indefinitely, it is possible the material temperature could rise until a thermal damage threshold is reached.

In Fig. 2d, short pulses with high repetition rate may result in a gradual increase in material temperature in a similar fashion caused by continuous wave (cw) beams as shown in Fig. 2e. In these cases, one could expect damage to the optical surface once a temperature threshold is breached. Such thermal processes include material thermal expansion, thermally induced strain, or the material reaching its melting point.

Because material damage caused by laser irradiation may occur in any of the above mentioned scenarios, LIDT values must be reported under very specific test conditions.

There are many factors which could significantly reduce the LIDT value of a material surface such as the presence of scratches, pores, inclusions, dust or other contaminates. Therefore, it is important to ensure cleanliness of a component prior to measuring LIDT or using it in a laser application.

Terms, units, and standards for LIDT

As explained above, LIDT depends upon a variety of operating conditions such as those depicted in Figs 2a – 2e. The laser beam may be pulsed, cw, or pulsed with high repetition frequencies, sometimes referred to as "quasi-cw". Thus, the ISO 11254-1 and 11254-2 standards have been developed for testing at conditions involving single pulses (referred to as "1-on-1 tests") or multiple pulses (referred to as "S-on-1 tests")

Symbol	Term	Units	Definition or Relationships
λ	Wavelength	nm	laser's wavelength
τ	Pulse Duration	sec	FWHM of the optical power versus time
R	Pulse Repetition Rate	Hz = sec^{-1}	number of pulses per sec
T	Time Interval Between Pulses	sec	$T = 1/R$
P_{av}	Average Power	Watts (W) = J/sec	$P_{av} = E/T$
P_{pk}	Peak Pulse Power	Watts (W) = J/sec	$P_{pk} = E/\tau$
A	Laser Spot Area	cm^2	see discussion in the current section
E	Energy Per Pulse	J = joules	the total energy of a single pulse
F	Fluence or Energy Density Per Pulse	J/cm^2	$F = E/A$
I	Intensity or Power Density	W/cm^2	$I = P_{av}/A$
I_{max}	Maximum Intensity or Power Density	W/cm^2	$I_{max} = P_{pk}/A$

Table 1: List of relevant terms and units used for LIDT computations and measurements.

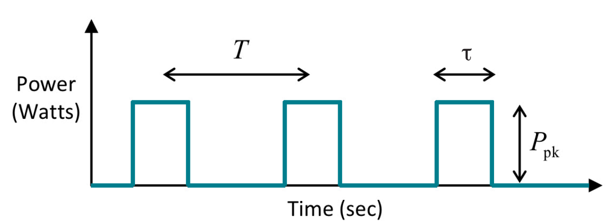

Fig. 3: A pulse train with rectangular temporal profiles.

respectively. IDEX Optics & Photonics (IOP) coated test samples are usually tested using the S-on-1 test method.

In order for one to apply measured LIDT values to the particular laser beam characteristics of an intended application, it is necessary to get acquainted with key terms and units used in LIDT tests. Table 1 provides such a list, and Fig. 3 is a simple illustration highlighting what these terms mean for a beam whose temporal profile consists of a train of rectangular pulses. Note also that these terms are consistent with the LIDT concepts discussed in ISO 11254-1 and 11254-2.

LIDT values for pulsed lasers are often expressed in terms of energy density. From Table 1, this is the pulse "fluence", with units of J/cm^2. For pulse trains with rectangular temporal profiles such as in Fig. 3, fluence is computed by multiplying the peak power P_{pk} by the pulse duration τ and dividing by the spot size A. For a beam consisting of pulses with Gaussian or "Gaussian-like" temporal profiles (Fig. 4), the computation for the energy per pulse depends on the definition of the pulse duration. If, for example, the pulse duration were defined by the 1/e^2 (where e = 2.71828…) power level of the Gaussian profile as shown in Fig. 4, then the total energy contained within this pulse is the definite integral of the Gaussian temporal profile over an infinite time which we may write as:

$$E = \int_{-\infty}^{+\infty} P_{\text{pk}} \exp\left[-\frac{t^2}{(\tau/2)^2}\right] dt \,. \qquad \textbf{Eq. (1)}$$

To integrate the right side of Eq. (1), we make use of the fact that:

$$\int_{-\infty}^{+\infty} \exp\left(-ax^2\right) dx = \sqrt{\frac{\pi}{a}} \,. \qquad \textbf{Eq. (2)}$$

Doing this, Eq. (1) becomes:

$$E = \frac{\sqrt{\pi}}{2} P_{\text{pk}} \tau \,. \qquad \textbf{Eq. (3)}$$

Conversely, if the total energy per pulse with a Gaussian temporal profile is known, then Eq. (3)

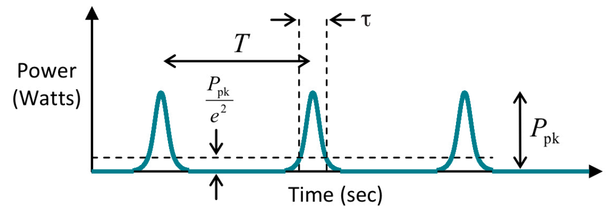

Fig. 4: A pulse train with Gaussian temporal profiles.

provides a means for computing the peak pulse power, provided that the pulse duration is defined at the 1/e^2 power level.

Due to ambiguities in the definition of pulse duration, the ISO 11254-2 standard has introduced the term "effective pulse duration", defined as the ratio of pulse energy to the peak pulse power. The effective pulse duration for a pulse with a Gaussian temporal profile is ($\sqrt{\pi}/ 2$)xτ. This is a convenient definition when applied to pulses with Gaussian temporal profiles, because multiplying the peak power by the effective pulse duration leads to Eq. (3).

Now, the question arises as to how to compute the laser spot area A of a beam. If the spatial intensity profile of the beam is a circular uniform "top-hat" distribution with a well defined beam diameter, then the area is $\pi \times d^2/4$ where d is the beam diameter.

If the spatial profile is that of a typical Gaussian TEM00 mode beam, then the ISO 11254-2 standard defines the beam's "effective area" to be the following:

$$A_{\text{eff}} = \frac{\pi d^2}{8} \,, \qquad \textbf{Eq. (4)}$$

where d is the beam diameter defined at the 1/e^2 intensity level (similar to Fig. 4 except that time is replaced by a spatial coordinate on the horizontal axis, and power is replaced by intensity on the vertical axis). Dividing the beam's total pulse energy by this area gives the fluence. For example, if a pulse train consisted of pulses with Gaussian temporal profiles, then the total energy per pulse is given by Eq. (3). If this beam's spatial intensity profile is a Gaussian TEM00 mode beam, then dividing Eq. (3) by (4) yields:

$$F = \frac{E}{A_{\text{eff}}} = \frac{P_{\text{pk}}}{2}\tau\sqrt{\pi} \times \frac{8}{\pi d^2} = \frac{4}{\sqrt{\pi}}\frac{P_{\text{pk}}\tau}{d^2}. \qquad \text{Eq. (5)}$$

The reason for the definition given in Eq. (4) for a TEM00 mode beam is clear when we note that such a beam's spatial intensity profile may be written as:

$$I(x,y) = I_{\max}\exp\left[-2\frac{(x^2+y^2)}{(d/2)^2}\right]. \qquad \text{Eq. (6)}$$

For a beam consisting of a pulse train, the peak pulse power is the total power contained in the beam's entire spatial profile. Thus, this total power is given by the integral of Eq. (6) over an infinite space:

$$P_{\text{pk}} = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} I_{\max}\exp\left[-2\frac{(x^2+y^2)}{(d/2)^2}\right]dxdy \qquad \text{Eq. (7)}$$

Making use of Eq. (2), Eq. (7) may be re-written as:

$$P_{\text{pk}} = I_{\max}\frac{\pi d^2}{8}. \qquad \text{Eq. (8)}$$

Since power is the product of intensity and area, the factor which multiplies intensity in Eq. (8) is given by the effective area defined in Eq. (4). Thus, the area defined in Eq. (4) has been created uniquely for beams with Gaussian (TEM_{00} mode) spatial intensity profiles.

For spatial intensity profiles that are anything other than uniform or Gaussian (i.e., with a number of hot spots within the spatial profile), there are no straightforward means for computing the effective area. In such cases, one must empirically determine the smallest area of the beam which contains the most energy in order to compute the maximum pulse fluence.

Finally, since LIDT values may be reported for cw beams or pulsed beams at various repetition rates, it is necessary to know whether or not to compute your beam characteristic in terms of intensity (W/cm^2) or fluence (J/cm2). Table 2 provides a simplified classification.

As an example, suppose a frequency-doubled Nd:YAG laser at 532 nm emits 10 ns pulses at a 10 Hz repetition rate, with an average power of 1 W. This laser is a long pulse beam, and the relevant LIDT units are J/cm^2. Therefore, in order to compare this beam's characteristic to measured LIDT values, one should compute the beam's fluence. Since the average power is 1 W, we can make use of its definition from Table 1 to compute for the pulse energy E = P_{av} × T = 1 W × 0.1 sec = 0.1 J or 100 mJ. If the beam is focused down to a 1 mm spot diameter (and if it is a circular uniform beam), then the fluence computes to about 13 J/cm^2. Thus, in this case, one hopes to find a coating with an LIDT > 13 J/cm^2.

Type of Beam	Typical Pulse Properties
Long-pulse beam	τ ~ ns to µs R ~ 1 to 100 Hz
Continuous wave (cw)	Continuous output
Quasi-cw beam	τ ~ fs to ps R ~ 10 to 100 MHz

Table 2: Classification of beam characteristics.

For illustrative purposes, one may wish to compute the peak power in the beam. This is equal to the power per pulse (which is equal to the previous computed pulse energy of 100 mJ) divided by the pulse duration of 10 ns. Thus, the peak power = 0.1 J/10 ns = 10 MW.

LIDT values for IDEX Optics & Photonics coated optical components

IDEX Optics & Photonics (IOP) components span a broad spectrum of well-recognized brands. These include CVI Laser Optics, Semrock, Melles-Griot, and Advanced Thin Films (ATFilms and Precision Photonics). Most IOP LIDT values may be found on the websites and catalogs of the various brands. As an example, CVI Laser Optics LIDT data is provided in Table 3.

Optic Type	0% fail conditions	50% fail conditions
1064 nm		
High reflectivity coating at 450°	30.1 J/cm^2 in 20 ns*	> 50 J/cm^2 in 20 ns*
High reflectivity coating at 0°	23.7 J/cm^2 in 20 ns*	> 50 J/cm^2 in 20 ns*
50% reflectivity coating at 0°	17.7 J/cm^2 in 20 ns*	50 J/cm^2 in 20 ns*
Anti-reflective coating at 0°	10.8 J/cm^2 in 20 ns*	30 J/cm^2 in 20 ns*
268 nm – 850 nm		
High reflectivity coating (750-850nm) at 45° s-pol	4 J/cm2 in 300 ps avg power, 8 J/cm^2 in 300 ps peak power	7 J/cm^2 in 300 ps avg power, 14 J/cm^2 in 300 ps peak power
High reflectivity coating (694nm) at 45°	1.4 J/cm^2 in 30 ns**	62 J/cm^2 in 30 ns**
50% reflectivity coating (694nm) at 0°	24 J/cm^2 in 30 ns**	74 J/cm^2 in 30 ns**
High reflectivity coating (532nm) at 0°	9.7 J/cm^2 in 10 ns*	15 J/cm^2 in 10 ns*
High reflectivity coating (355nm) at 45°	4.6 J/cm^2 in 10 ns*	6.88 J/cm^2 in 10 ns*
97% reflective coating (268nm) at 45° s-pol	2 J/cm^2 in 60 ns****	3.4 J/cm^2 in 60 ns****
193 nm		
High reflectivity coating at 0°	4.3 J/cm^2 in 15 ns (1-on-1)***	1.54 J/cm^2 (1000 on 1)
High reflectivity coating at 45°	2.63 J/cm^2 in 15 ns (1-on-1)***	1.17 J/cm^2 J/cm^2 (1000 on 1)
Anti-reflective coating on CaF_2 at 0°	1.10 J/cm^2 in 15 (1-on-1)***	0.81 J/cm^2 (1000 on 1)

** Multiple shot (200 shots) with 20 Hz repetition rate*
*** Multiple shot (10 shots) with 0.2 Hz repetition rate*
****Multiple shot with 100 Hz repetition rate*
***** Multiple shot (100 shots), LDT value is arithmetic average of lowest damage and highest survival power*

Table 3: CVI Laser Optics LIDT data.

Scaling of LIDT test data

At pulse durations on the order of approximately 1 ns to 1 μs or more, it is generally observed that LIDT test data scales proportionately with the square root of the pulse duration, and directly with wavelength. This dependence is useful for situations where the LIDT value is known for an optical coating at a given wavelength and pulse duration, but the intended application for this coating involves another wavelength and pulse duration. Thus, one may write the scaling computation as follows:

$$\mathrm{LIDT}_2 = \mathrm{LIDT}_1 \times \frac{\lambda_2}{\lambda_1} \times \sqrt{\frac{\tau_2}{\tau_1}}, \qquad \text{Eq. (9)}$$

where the subscripts 2 and 1 denote the sought LIDT and reported LIDT values respectively.

As an example, let's take a look at the LIDT for a CVI high reflectivity coating at 0° angle of incidence at 1064 nm in Table 3. At 0% fail conditions, the value for this LIDT is 23.7 J/cm^2 at a pulse duration of 20 ns and 20 Hz repetition rate. Now, suppose we were using this same coating for a laser at the wavelength of 532 nm, 0° angle of incidence, 10 ns pulse duration, and at the same repetition rate. According to Table 3, the measured LIDT value is 9.7 J/cm^2. However, suppose that we did not have this value available. Using Eq. (9). We find:

$$\mathrm{LIDT}_2 = 23.7\ \mathrm{J/cm}^2 \times \frac{532\mathrm{nm}}{1064\mathrm{nm}} \times \sqrt{\frac{10\mathrm{ns}}{20\mathrm{ns}}} = 8.4\ \mathrm{J/cm}^2 .$$

As expected, this value is fairly close to the measured value of 9.7 J/cm^2.

New products for femtosecond applications

Traditionally high-LIDT, low dispersion mirrors were limited in the broadness of the reflectivity band. A broader reflectivity band can be achieved by using a higher refractive index film material such as TiO_2 but this material choice tends to reduce the damage threshold.

CVI Laser Optics has actively researched methods of combining a broad reflectivity band and low dispersion with the benefits of a high LIDT optic. The positive results, compared to existing products, are shown in Figs. 5 and 6.

While there are many established options for testing with ns pulses, fewer exist for testing with shorter pulses. The LIDT has been tested for the mirror in figures 5 and 6 by Prof. Jean-Paul Chambaret of Applied Optical Laboratory in Palaiseu, France, using a 200 ps pulse. The LIDT of the broadband-low dispersion mirror matches the LIDT of the existing, traditional high-LIDT mirror.

These new mirrors are available for all Ti:Sapphire laser-related center wavelengths.

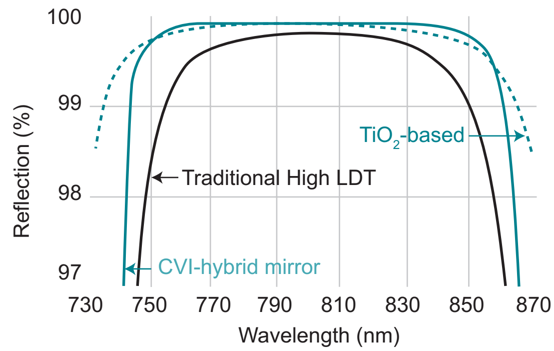

Fig. 5: A comparison of Reflectivity vs. Wavelength of TiO_2-based traditional high laser damage threshold (LDT), and the new CVI-hybrid mirror.

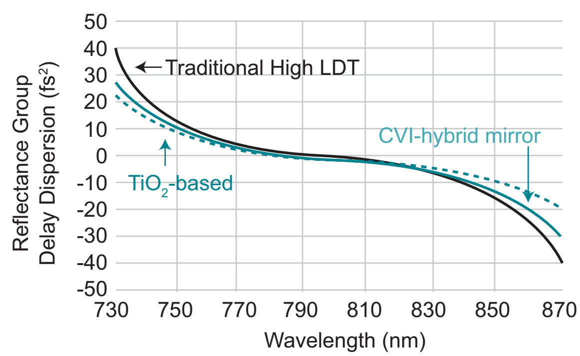

Fig. 6: A comparison of Reflectance Group Delay Dispersion vs. Wavelength of TiO_2-based, traditional high LDT, and the new CVI-hybrid mirror.

New developments in high power UV Excimer, Ti:Sapphire and Nd:YAG laser optics

Recently there has been rising demand for high power laser optics with large coated apertures. In the past, high LIDT coatings for UV applications at 308 nm or below could only be deposited over small apertures in order to avoid crazing of the coating. CVI Laser Optics has developed a coating technique where the coated aperture is only limited by the size of the coating chamber. We have successfully coated UV optics with diameters up to 235 mm, and Ti:Sapphire and Nd:YAG optics with diameters up to 500 mm.

CVI Laser Optics is continuing work improving damage threshold, increasing coated aperture, and maximizing reflectivity for optics ranging from 193 nm to 2200 nm.

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