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Laser damage you can trust

HIGH POWER PULSED AND CW LASER DAMAGE

Understanding the differences in Pulsed and CW damage

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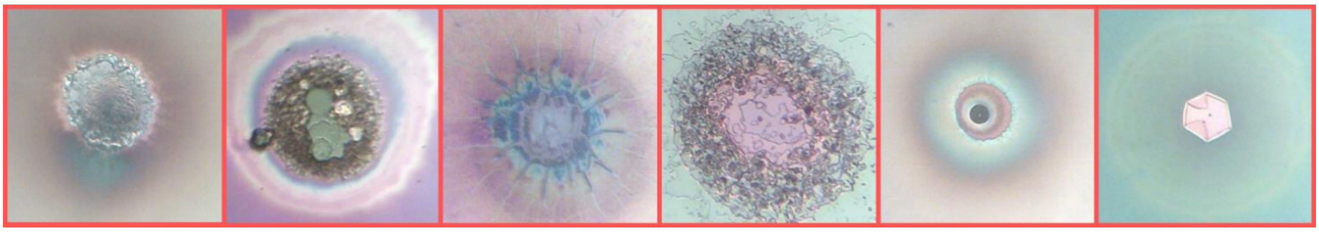

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INTRODUCTION

All of us who work with high power lasers have experienced laser damage, usually when we least wanted to. Sometimes just an unexpected flash of light means an optic needs to be replaced, but often the case is far worse where a single coating damage can lead to systemwide failure. Much of our work is certifying optics for pulsed laser systems in order to prevent this kind of catastrophic event.

In recent years we have had increasing requests for CW testing. These optics are used mainly in manufacturing and medical sectors, where again damage failure is expensive. As output powers have increased damage is increasingly prevalent and certifying CW optics has become more imperative. They appear to damage at lower power levels than expected from their performance and threshold values in a pulsed system. We report here a study of different substrate materials in terms of pulsed and CW performance as given by their Laser Induced Damage Threshold (LIDT) values. The LIDT value denotes the max power density (or in the case of CW, the maximum linear power density) an optic can withstand without damaging.

INDUSTRY GROWTH

Progress of our laser industry in terms of laser power and wavelength range has followed the capability of coaters to improve their optics via improvements in optical coating technology. The industry standard for assessing the quality of a coating is its resistance to applied power i.e. its LIDT. The higher the damage threshold, the better the laser component, the more power it can take and so the scope opens for more powerful laser production. In the past two decades, hand in glove with an explosion of new laser technology, is substantial progress in high precision coating technology. Included in this step-function improvement is the production and subsequent preparation of precision grade substrates.

Advances in substrate polishing, surface pacification, etching and cleaning have taken on new techniques and processes . Many of these highly controlled clean deposition and defect elimination technologies were initially developed for custom monolithic and heterogenic wafer bonding in microelectronics fabrication technology[1].

CONTINUOUS WAVE (CW) LASER GROWTH

CW radiation interacts with optics in a very different way to pulsed radiation. The damage mechanism is also very different from the pulsed counterpart. This was not fully understood until collaborative work done in 1996 gave a comprehensive account of the factors affecting CW laser damage[2]. These studies devised the concept of linear power density allowing CW damage results to be scaled to individual requirements. The work was further recognised and incorporated into the ISO standards for CW laser damage. Since this discovery, accurate CW laser damage testing has been possible and it has led to the growth of applications and industrial pick up of CW lasers. Globally we now have CW laser systems exploiting numerous new applications and replacing heavy industrial machinery in material processing with systems of increasing precision and capability[3].

HOW PULSED AND CW DAMAGE DIFFER

a. Pulsed Damage

When pulsed laser damage is performed, the key factor in damaging the optic is peak power density (PPD) W/cm^2 (peak fluence per unit time) which is the quantity being assessed in *pulsed* laser damage threshold testing[4,5]. The ISO definition of laser damage is: "Any permanent laser-radiation-induced change in characteristics of either the substrate or the coating". The ISO standards rule on the method(s) of test set-up. They also have guidelines as to the spatial periodicity of test sites and the repetition required for statistical accuracy. As coatings and most substrates are amorphous in character their response to radiation is not as repeatable as crystalline materials.

Thus damage testing protocol is engineered to give maximum accuracy by numerous repetition. Factors such as several pulses per site (S-on-1), repetition of sites at the same power level, spacing of the sites and lower limits imposed on spot size etc., all go toward giving an accurate and repeatable result. The spacing of sites give accreditation to the ability of the laser radiation to effectively anneal the sample.

Annealing artificially elevates the damage threshold and in some cases this effect is substantial. The diagram below (Fig 1) shows the test pattern for an ISO (S-on-1) test. As the power increases so does the number of damage events.

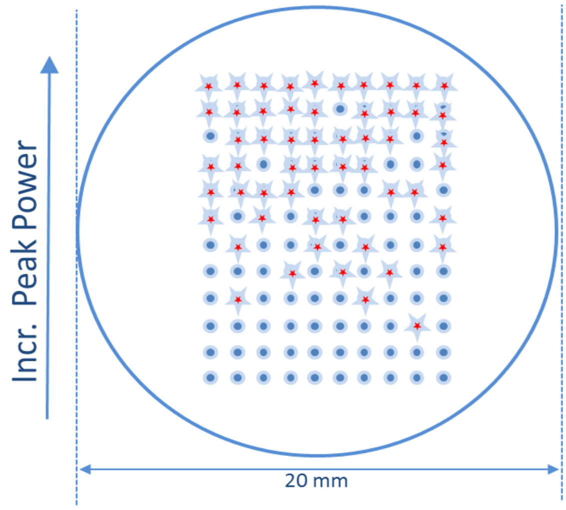

Fig.1

This technique applies to both pulsed and CW tests. Onset of damage is the most important point below which the optic is safe to use. In cases where a graphical analysis is possible then even if the first (very small) damage event is missed, we still get the true threshold. When we graph the results shown in Fig.1 as damage probability vs. PPD, the threshold value is the x-axis intersect.

The graphical analysis in Fig. 2 is an idealised depiction, whereas real tests give more scatter as the test material is amorphous.

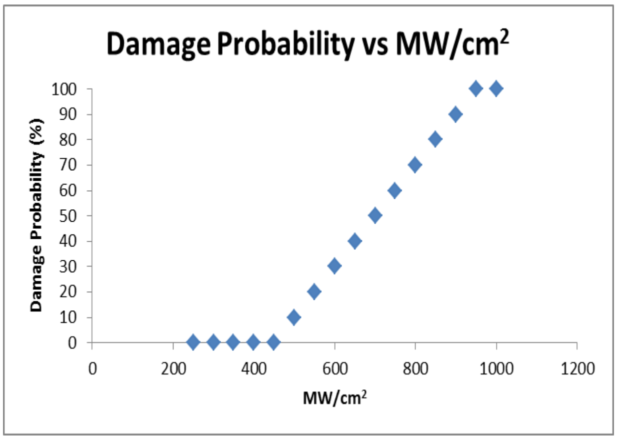

Fig. 2

In practice we only consider results as graphical when a linear fit, with a high coefficient of regression ($R^2 > 0.95$), can be achieved.

The above material based considerations are applicable to both pulsed and CW testing and are devised to give a true threshold result. Annealing is one particular source of laser damage testing error which allows the coater to think his coating is better than it is (numerically). Annealing is induced when the site to site separation is reduced from ISO guidelines. Large "test site separation" safeguards against annealing which artificially raises the threshold value. We tested if annealing was also present in substrate tests as well as in the better known coated optics case. We took separate Crystalline Quartz samples and purposely annealed them by placing the target sites 1.5 x the laser spot diameter apart. ISO guidelines advise a site separation of 2 to 3 times the spot diameter. By closing the gap we effectively annealed a subsequent site within close proximity of the incident target site. The results gave elevated threshold values of the order of 25% as detailed in Table 1.

All the above criteria show the similarities for testing pulsed and CW optics but the difference is evident from a number of standpoints. The root cause of all these differences lie in the respective damage mechanisms. Laser damage onset translates as breaking of the weakest molecular bonds which are most frequently located at the coating/substrate interface. Damage can also occur on the optic surface, but this is less likely in precision optics where great care is taken to keep a pristine surface. In complex coatings with many layers, the picture is less clear. Factors affecting the location of initial pulsed laser damage are :

- Polishing grades of a substrate as shown in Fig. 3 below, can be supplemented by subsequent etching including plasma and remote plasma techniques.
- Substrate cleaning procedures
- Inclusions within the substrate surface
- Coating deposition affinity for the substrate surface, i.e. coating to substrate bonding
- Interlayer bonding within coating layers
- Stress on the surface (compressive or tensile)
- Surface structures can be open, or low density; these are stress-relaxed structures dictated by the coating method. They tend to have very high threshold values however they also tend to degrade over time being prone to poisoning.
- Denser surfaces are in general deposited by traditional techniques and have lower LIDT values. However, we are still talking here of high-end optics which exhibit four or five times the LIDT values of standard catalogue optics.
- Subsequent treatments such as annealing give elevated threshold values, especially when laser annealed. Here the source energy penetrates through the coating and saliently through the substrate-coating interface, strengthening the most vulnerable bonds.

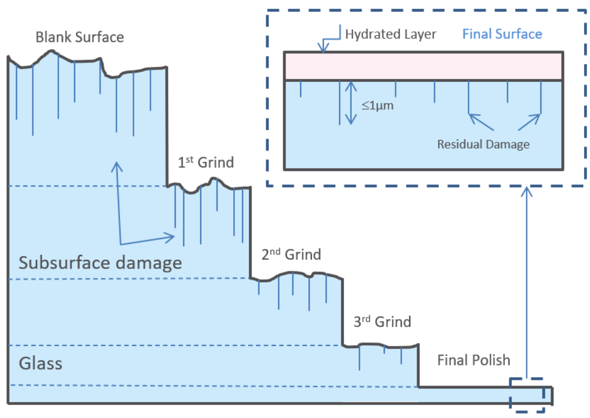

Fig. 3

All the above factors affect the threshold value. The pulsed damage mechanism is wholly dependent on bonds breaking. This is in part a function of their resonance frequency which is why absorbents are wavelength specific. The damage is dependent on the rate of energy delivered i.e. the power per unit area. Heat dissipation is not a primary factor here as the time between pulses is generally of the order of 10^6 times longer than the pulse duration. In the case of very high rep rates or very long pulse durations then a CW test is more appropriate.

b. CW Damage

One technical difference in performing CW tests is the size of damage area incurred. Once damage starts on any particular site, the radiation to that site is stopped in order to avoid sputtering and subsequent site contamination. However the greatest technical difference is the length of time the sample is exposed to radiation.

Accuracy in CW testing dictates each site is allowed to reach thermal equilibrium. If no equilibrium is reached then incident average power is above its threshold limit and it will damage. A complete CW threshold evaluation will take many hours to complete and is substantially more expensive than its pulsed counterpart. Another time limiting factor is the requirement to keep the laser in a steady state operating condition. Constant monitoring of the laser's output characteristics gives the information required to limit its use. Working with CW radiation for diagnostic measurements is more demanding than its pulsed counterpart.

Continuous wave damage is dominated by an entirely different mechanism to pulsed laser damage. The level of incident power is far below that required by a minor defect to initiate damage. The average damage threshold value is in the region of 100s of kilo Watts for CW tests as opposed to Giga Watts normal in pulsed testing.

"The term 'defect' here is misleading when glasses are considered. Most physicists and solid state scientists experience defects as representing discrete electronic states within the band gap. And indeed all physical defects do produce such states. However the physical structure of amorphous materials (glasses) give rise to tail states which are states within the band gap tailing away from the band edges. Even the best glasses have these states as their presence is an inherent characteristic of a glass or amorphous structure."

The key factor in whether or not an optic damages when exposed to CW radiation, is how fast it can dissipate the continuously applied heat. In this case unlike pulsed damage, threshold values depend on:

- Average power
- Thermal diffusivity[6]
- Thermal conductivity
- Thermal gradient
- Test beam (spot) diameter
- The steady state region where the optic can take continuous radiation without building up heat and without sustaining change.

CW damage testing is also used for very long pulse durations and high repetition rates, where the time gap between pulses is equal to or smaller than the thermal diffusivity.

For the first time we encounter linear power density which is the average power per spot diameter W/cm[7]. A small test spot can lose heat quickly as the entire area around it presents a steep thermal gradient. Conversely a large test spot experiences a very different thermal environment as the centre of the test site sees little or no thermal gradient surrounding it. Here heat dissipation is more difficult and heat accumulates more easily. Hence CW damage is spot-size dependent; the larger sites are more easily damaged than smaller ones given the same fluence. CW damage results are given in units of linear power density W/cm. This is a measure of incident average power per spot diameter in centimetres.

Below is a ready reckoner that we give as standard with all CW test reports. An example is given in Table 1 and Fig. 4, where the threshold has been determined as 100kW/cm. The ready reckoner allows a quick method of scaling your threshold to you own laser beam size.

Ready Reckoner For LIDT Value = 100 kW/cm		
Your Spot Size	Your Spot Size (cm)	Safe Max Ave P (kW)
25 microns	0.0025	0.25
50	0.005	0.5
100	0.01	1
200	0.02	2
400	0.04	4
800	0.08	8
1 mm	0.1	10
2	0.2	20
4	0.4	40
8	0.8	80
1 cm	1	100
2	2	200
3	3	300
4	4	400
5	5	500

Table 1

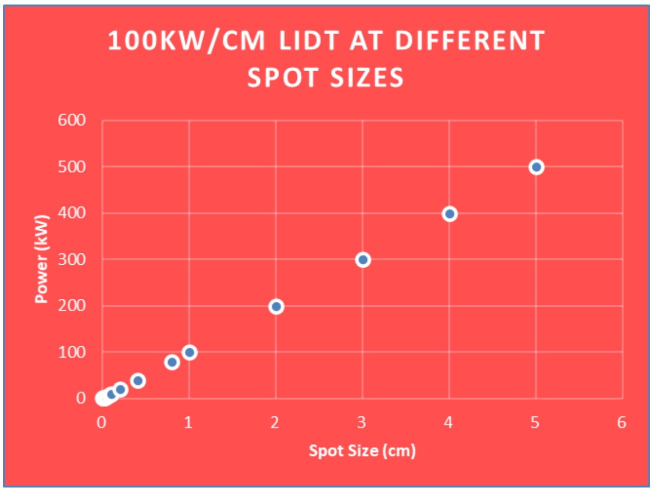

Fig. 4

BRL includes a ready reckoner appropriate to the customer's threshold results.

c. CW vs. Pulsed: The Values & The Units

Whereas a pulsed LIDT test on an AR coated optic can give a peak power density threshold of 3000 MW/cm^2 its CW test on the same sample can be as low as 100kW/cm. We seek to illuminate an important factor, which although inherent, is not well communicated in most damage texts. The pulsed value is given in units per pulse and within that it is the value of the peak radiation per pulse. To labour this point we take the pulse energy and divide it by the pulse duration to get the average pulse power, we then take the beam diagnostic and extract the peak power per area, giving the result in MW/cm^2 for each pulse. If we were to take the average value of that radiation (per second not per nano-second and account for the peak area), the above value of 3000 MW/cm^2 reduces to single figures of average Watts. So the values of pulsed and CW threshold tests cannot be compared at all. This is further borne out by their relative units being different. Thus a CW damage test result cannot be predicted or calculated by using a pulsed LIDT value.

We tested a number of substrate materials fabricated to the same sample dimensions with a range of different surface qualities. Although threshold values for the same coating can vary remarkably between test houses, the threshold values for substrate materials tend to be in line for all the major test houses[8]. We tested these samples as described on our website via ISO standard pulsed and CW techniques[9]. We found variations between qualities and between materials in both types of test. The CW results tended to vary with the material softening point concurring with academic research[10].

It is our experience since launching our new CW test facility that there are subtle differences between pulsed and CW LIDTs. The relationship of coated samples' LIDTs to their respective substrates' LIDTs reverses from CW to pulsed. Whereas in pulsed damage tests it is very difficult to get a coating to enhance (raise) the threshold above that of the precision polished substrate, in CW tests this is very common. HR coated samples in the region of 225kW/cm have been measured here and AR optics exceeding this have also been tested, but again resilient substrates do play a part.

Material	Pulsed MW/cm2	Pulsed J/cm2
n-BK7 S1	3400	68
n-BK7 S2	3050	61
n-BK7 S3	3000	60
Infrasil S1	4500	90
Infrasil S2	4400	88
Infrasil S3	3850	77
Fused Silica S1	5550	111
Fused Silica S2	5400	108
Fused Silica S3	4750	95
Moth-eye	3500	70
Moth-eye	3760	75.2
X Quartz Annealed	7190	143.8
X Quartz S1	5800	116
X Quartz S2	5300	
X Quartz S3	5000	100

Table 2 Pulsed LIDT Results

The range of silicate-based substrates we tested are common in precision laser optics; n-BK7, Fused Silica, Infrasil and Crystalline Quartz. Along with these standards we tested "Moth-eye" substrates. These have sub-wavelength anti-reflection (AR) nanostructure patterns etched on the surface of high purity Fused Silica. However the surfaces are easily poisoned and require clean-room condition handling.

The pulsed results varied as expected from their polishing qualities and their material properties. For example Fused Silica is harder than n-BK7 and is therefore easier to polish to a precision quality. Fused Silica has a Youngs modulus of elasticity = 7.25×10^{4} Nmm^{-2} compared to n-BK7 with a Youngs Modulus of 8.2×10^{4} Nmm^{-2}. Thus n-BK7 is harder to polish to the same grade as Fused Silica as it is more elastic.

The nuances of pulsed damage testing in this power region is that anything can nucleate a damage event. The key for accuracy in pulsed systems, at these elevated power levels is to understand the capability and performance of energy and pulse duration sensors.

The corresponding CW results are given in Table 2. Here the LIDT value follows the softening point trend of the substrate material. The softening temperature was not available for the "Moth-eye" substrates. These are basically Fused Silica with a nano-textured surface which would, due to its fine open structure, lend itself to softening at lower temperatures than Fused Silica with an optical grade polished surface. It gave nearly half the LIDT of its parent material.

SUBSTRATE	kW/cm	Softening Pt °C
INFRASIL	110.7	1730
CRYSTAL QUARTZ	95.0	1700
FUSED SILICA	94.8	1585
N-BK7	48.6	557
FS Moth-eye	47.4	unknown
FS Moth-eye	57.1	unknown

Table 3 CW LIDT Results

[1] Rona E Belford and Sumant Sood, "Surface activation using remote plasma for silicon to quartz wafer bonding", Microsystem Technologies: Vol. 15(3), 407 (2009).

[2] Rune Holm, Keith E. Puttick, Detlev Ristau, Urs Natzschka, George Kiriakidis, Nirmal Garawal, Eddie Judd, David Holland, David Greening, Nick Ellis, Mark Wilkinson, Miguel Garcia Pamies, Celestino Sanviti, Irene Cantoni, "CW/CO2 laser damage in optical components: thermal modeling and surface characterization," Proc. SPIE 2714, 27th Annual Boulder Damage Symposium: Laser-Induced Damage in Optical Materials: 1995, (27 May 1996); https://doi.org/10.1117/12.240413.

[3] https://www.spilasers.com/industrial-fiber-lasers/redpower/cw-laser-applications/

[4] https://www.laserdamage.co.uk/faq/

[5] ISO Standards 21254-1; 21254-2; 21254-3 and ISO-TR-21254-4 2011.

[6] ISO Standards 21254-1pp 2,4

[7] ISO Standards 21254-1p 5 & 13.

[8] https://www.newport.com/f/nanostructure-surface-windows

[9] https://www.laserdamage.co.uk/faq

[10] Exarhos, G. J., et al. eds. Laser-Induced Damage in Optical Materials: 2010, Proc. SPIE 7842 (2010).