Manx Precision Optics

Thermal Laser Induced Damage in Optical Coatings Due To An Incident Pulse Train, an overview

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1. INTRODUCTION

Laser Induced Damage Threshold (LIDT) of an optical component defines the maximum intensity the component can resist before the onset of laser damage and as a result is a critical parameter for any modern laser system, with the LIDT defining the maximum possible intensity. However laser damage is a multi-faceted and complex problem with multiple theoretical mechanisms depending on pulse duration, optical coating quality and the manufacturing process of the component. As multi-Petawatt systems become commonplace[1] and laser intensities approach the scale[2] of $10^{24}\mathrm{Wcm}^{-2}$, experimentally verified theories and models of laser damage as well as scaling laws become ever more important. Traditionally, LIDT in the nano-second pulse duration regime has long been thought to be due to intrinsic defects[3,4] within thin film interference coatings, arising as a result of the optical coating deposition process. These defects act as highly absorbing spots, heating the surrounding coating material to its softening or melting point. In the $\geq$ 1ns regime, LIDT/critical fluence approximately follows the scaling law[5] (1) when scaling from a beam of wavelength λ_1 and pulse duration τ_1 to a beam with properties λ_2 and τ_2.

$$F_{crit}(\lambda_2, \tau_2) = \sqrt{\frac{\tau_2}{\tau_1}} \frac{\lambda_2}{\lambda_1} F_{crit}(\lambda_1, \tau_1). \tag{1}$$

Despite decades of research however laser damage remains as something of a theoretical unknown as LIDT values are notoriously unreliable[6] or at times contradict common expectation. In this article the results of a thermal theory of laser damage presented at the SPIE Laser Damage Conference (2021)[Paper 11910-37] are explored.

Previous thermal models have focused on the role of individual intrinsic, microscopic defects absorbing energy from single pulses of sufficient intensity. The model discussed here is instead macroscopic in nature, accounting for the geometry and dimensions of the optic and beam. There is a greater emphasis on the

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heat diffusion capabilities of the film and substrate, the former of which may play a larger role due to the thermal conductivity of thin film coatings sometimes being orders of magnitude lower[4] than that of the bulk material. We focus primarily on the effects of long term bulk heating rather than damage due to singular pulses and account for the impact of repetition rate on LIDT.

It should be noted that a thermal model may be un-suitable for shorter pulses as damage in the femto-second or "ultra-short" pulse regime is thought to arise from different mechanisms. For example, damage (in dielectric coatings) may occur due to the excitation of valence electrons to the conduction band typically via multi-photon absorption for more energetic photons (i.e. UV) or through Tunnel Ionisation for less energetic photons[8] (i.e. IR). Thermal effects are less important in such regimes.

2. LASER INDUCED DAMAGE THRESHOLD

In this model, laser pulses are consecutively absorbed by an optical coating as depicted in figure (1). Each pulse induces a degree of heating within the coating which diffuses somewhat in-between each pulse. If the repetition rate of the laser is sufficiently high, the temperature of the coating will increase until the heat diffusing out of the film balances the heat entering the film entering thermal equilibrium. If the temperature at which this thermal equilibrium is achieved is above the critical temperature (for example the melting point of the coating materials), then the coating will suffer damage. The absorption and heating of the film is treated in terms of the macroscopic bulk of the film as opposed to studying the heating of individual, microscopic defects that are thought to initiate damage in most cases.

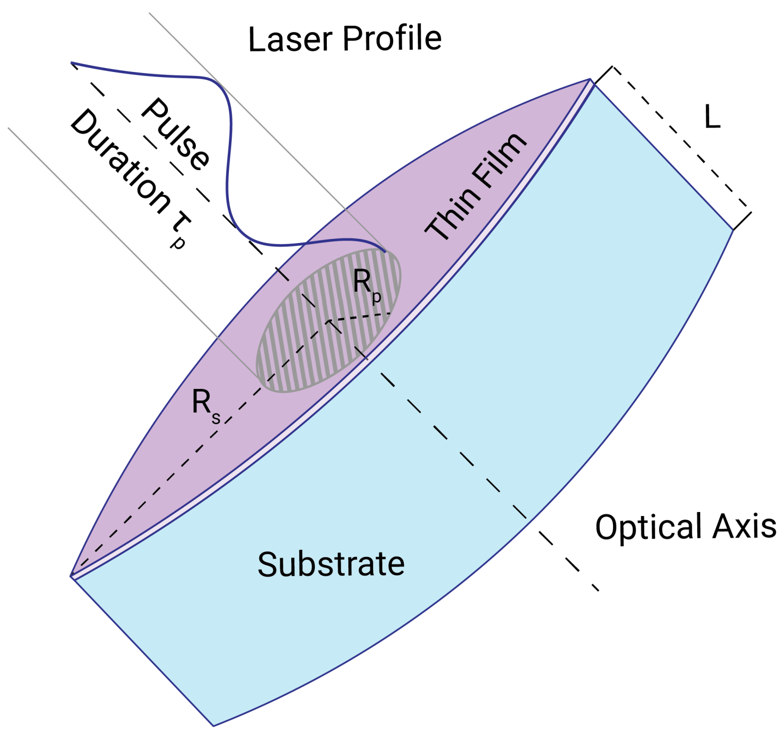

Figure 1. A radially symmetric beam of pulse duration τ_p incident upon an a coated substrate. The component has a radius R_s and a length L whilst the beam radius is R_p.

It is determined from the theory that the LIDT follows the rule (2) where F_{crit} is the fluence at which damage occurs. The expression naturally depends on a number of thermal properties such as critical temperature T_{crit}, thermal conductivity K_f, specific heat capacity c_f and density ρ_f. The square root dependence on the pulse duration and linear dependence on wavelength are in agreement with the well known experimentally verified scaling laws[5] (1) for pulse duration and wavelength. The dependence of (2) on thermal properties is also similar to a model discussed by A. H. Guenther in the context of laser damage,[4]

$$F_{crit} \propto T_{crit}\lambda\sqrt{K_f c_f \rho_f \tau_p} \cdot \xi. \quad (2)$$

The coefficient ξ varies from 0 to 1 and depends on the geometry of the beam and optic as well as the repetition rate. It can be viewed as the ratio of the maximum critical fluence the optic could withstand (for example for very low repetition rate the fluence is often maximised) to the current critical fluence.

3. GAUSSIAN PULSE LIDT

3.1 Impact of beam and optic geometry on LIDT

The critical fluence was found to have a complicated dependence on the beam and optic geometry. Assuming a Gaussian pulse structure, the ratio between the beam diameter and the optic diameter (denoted here as γ) is an important parameter for LIDT determination. The dependence of LIDT on γ is illustrated by the plots below.

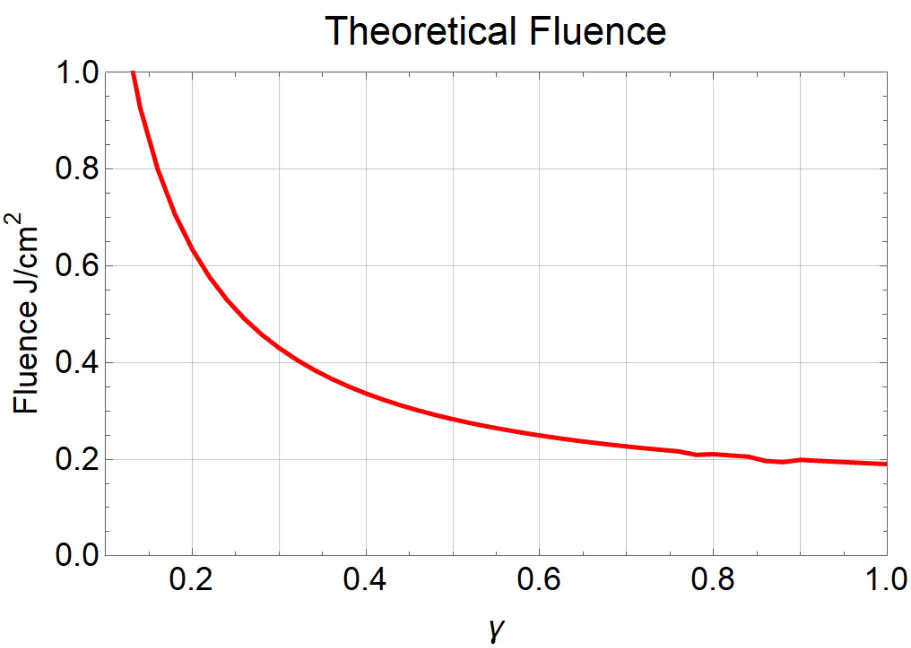

Figure 2. Critical fluence against γ, the Gaussian beam diameter divided by the optic diameter.

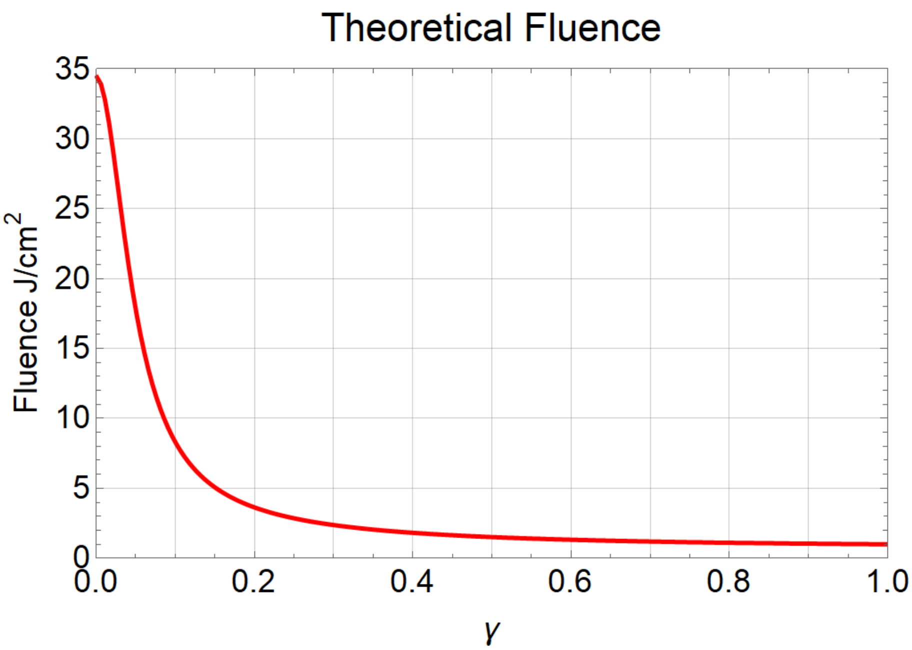

Figure 3. Critical fluence against γ at a lower repetition rate. Note how the curve peaks at $\gamma = 0$. This is the maximum critical fluence.

Figures 2 and 3 show how the LIDT drops off rapidly from its maximum at $\gamma = 0$. The decrease in fluence eventually flattens however once the beam and optic diameters are comparable. ISO laser damage testing standards[13] dictate that a minimum of 10 equally spaced test sites are to be chosen on an individual optic, meaning that the size of the beam is often small in comparison to the size of the test optic, with the minimum size being 0.2mm or 200μm. However the strong and complex dependence of LIDT on beam to optic diameter suggested by the theory implies that small spot laser damage bench testing may not be wholly representative of the behaviour of an optic in use i.e. with it's entire surface illuminated by the beam. It also suggests that a diameter square law[12] could vastly underestimate LIDT when scaling the spot size. Out in the field the laser beam diameter will almost certainly be of a size comparable to that of the optic and the scaling suggested by figures (2) and (3) may come into play especially if there is effective cooling at the boundaries of the optic.

It is worth briefly mentioning that there is an additional dependence on the absolute value of the substrate diameter as opposed to the value relative to the beam radius. Increasing the diameter whilst keeping γ fixed (i.e. scaling the beam with the optic) results in a lowered LIDT. This could be a problem for particularly large optical components (see figure (4)).

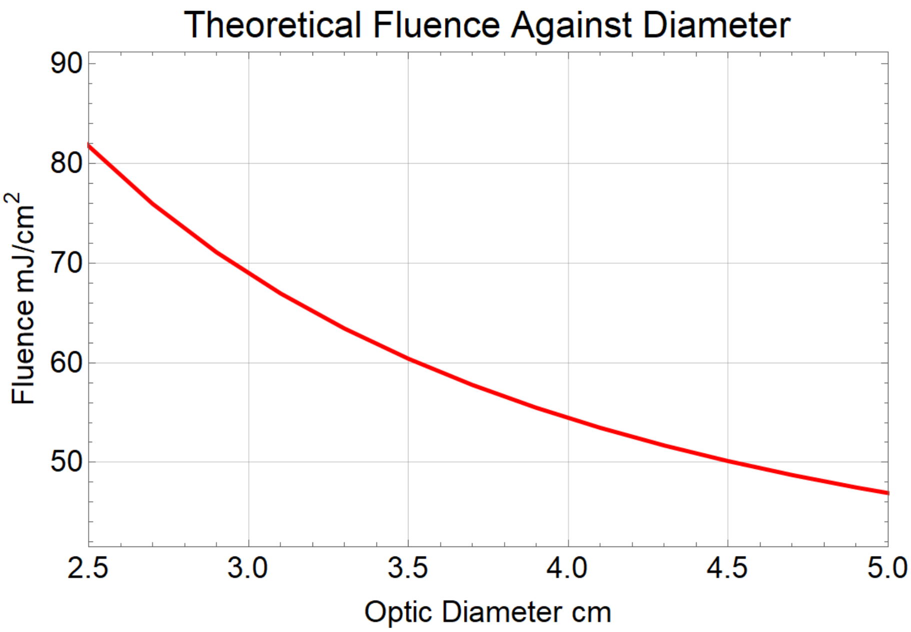

Figure 4. Critical fluence against R_s, the substrate diameter with fixed γ.

3.2 Repetition Rate Scaling

For sufficiently high repetition rate/low diffusivity, the repetition rate becomes an important parameter in LIDT determination. In the model the LIDT approximately follows an expression

$$F_{crit} \approx \frac{F_*}{1 + C_{\mathcal{R}}\mathcal{R}} \tag{3}$$

where $C_{\mathcal{R}}$ is a numerical constant and F_*. The dependence on repetition rate is illustrated below with some numerical examples.

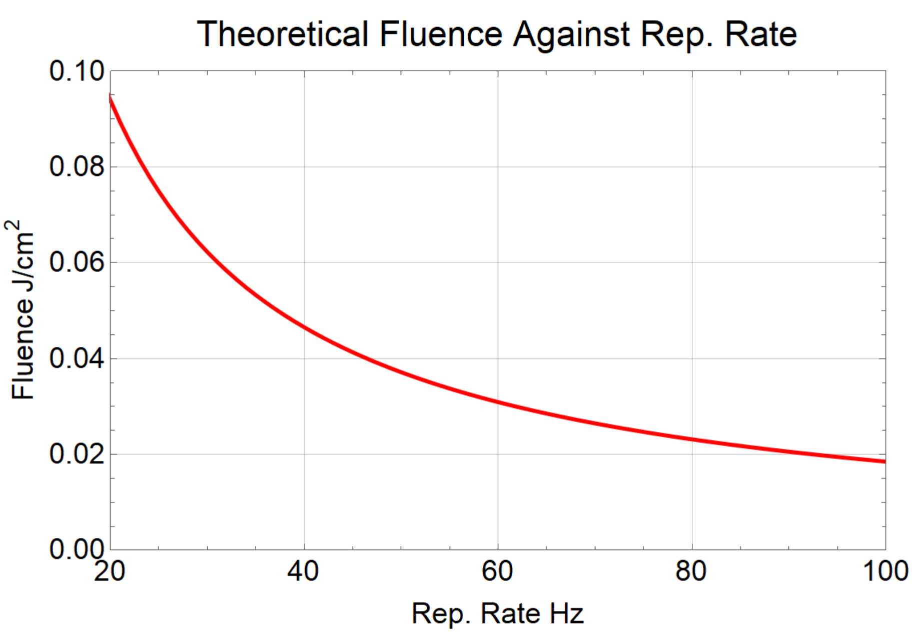

Figure 5. Critical Fluence against repetition rate for an optic with substrate and film properties similar to fused silica (SiO2).

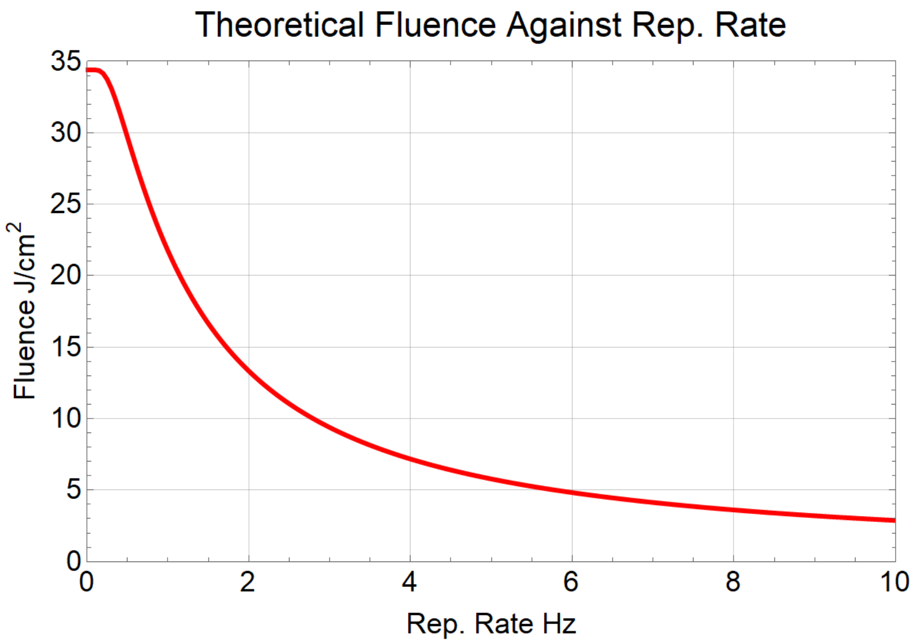

Figure 6. Critical Fluence against repetition rate for an optic with enhanced thermal diffusion.

The shape of the curve depicted in figure (5) suggests that a rule of the form (3) can be simplified even further in the right parameter regimes. It is fairly plain to see that in the case of a large repetition rate this collapses to the simple scaling rule (4) which does not require F_*

$$F_{crit}(\mathcal{R}_2) = \frac{\mathcal{R}_1}{\mathcal{R}_2} F_{crit}(\mathcal{R}_1). \tag{4}$$

When the repetition rate is very low the LIDT once again becomes equal to F_*. In the context of laser damage testing, F_* is most representative of the LIDT value obtained in the course of "1 on 1" laser damage tests whereby the LIDT is inferred from singular, high fluence pulses upon a target.[13] The general expression accounting for repetition rate, diameter ratios etc. is hence theoretically most accurate for "S on 1" tests where a target is bombarded with multiple pulses.

4. TOP-HAT PULSE PROFILE

So called "Top-Hat" profile pulses are another common beam geometry that have somewhat different behaviour in comparison to their Gaussian counterparts. Top-hat pulses are characterised by uniform irradiation over the area of the beam. The radial profile of a top-hat pulse is compared to that of a Gaussian in figure (7).

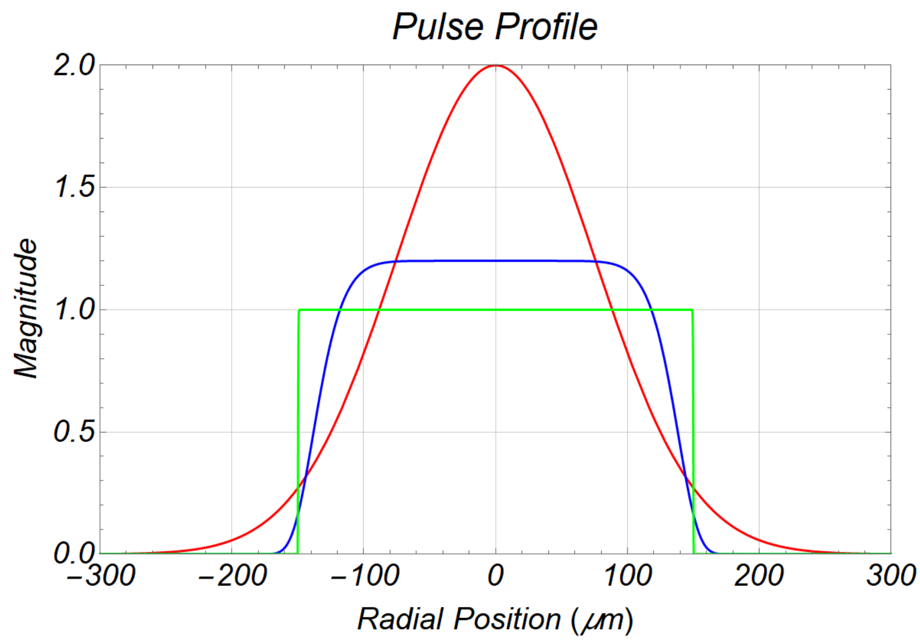

Figure 7. Radial profile of Gaussian, Super Gaussian and top-hat beams of beam diameter 300μm compared. The red curve represents a regular Gaussian pulse, the blue represents a Super Gaussian of order 10 and the green curve is an ideal top-hat profile.

Note how the top-hat has half the peak intensity but is much more spreadout than the Gaussian despite having the same power and effective optical area.

4.1 Beam To Optic Diameter Ratio

Top-hat pulse LIDT has the same form (2) and obeys similar trends to its Gaussian analogue with respect to γ. Below is a comparison of Gaussian and Top-Hat LIDT versus the beam to optic diameter ratio.

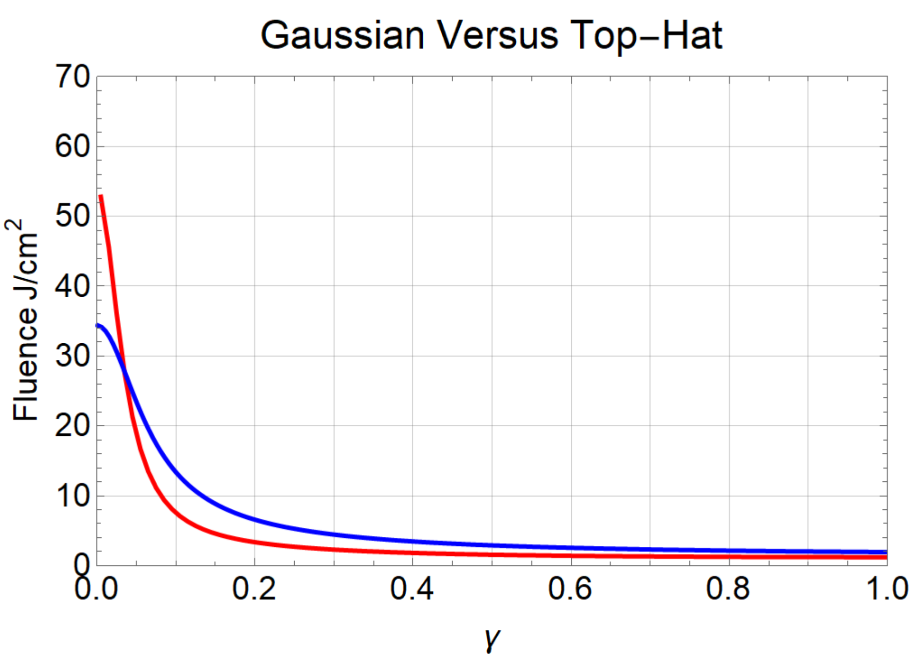

Figure 8. Critical fluence against γ for both Gaussian (blue) and Top-Hat (red) pulse structures. The Top-Hat pulse has a higher maximum critical fluence than the Gaussian case. The overall dependence of both critical fluences on γ is similar.

Studying figure (8) it is observed that generally speaking the critical fluence of the Gaussian is somewhat

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better than the Top-Hat case. This can be explained by referring to figure (7). While the peak power of a top-hat beam is around half that of a Gaussian analogue it is more uniform which is reflected in its temperature distribution. This means that heat from the centre of the optic has a harder time escaping as the gradient is not as steep. Therefore it will accumulate more heat resulting in a lower LIDT. When the beam diameter is either very small and/or the repetition rate is very low (such that damage is induced by a single pulse), the long term diffusion effects are less important and the lower overall peak intensity of the top-hat beam results in a better LIDT relative to its Gaussian counterpart. In the case of figure (8, maximum critical fluences are around 54Jcm^{-2} and 34Jcm^{-2} for the Top-Hat and Gaussian cases respectively.

5. CONCLUSIONS

The theory we have presented and discussed has interesting implications for the Laser Induced Damage Thresholds and its dependence on system parameters. Of special focus is the dependence on beam diameter and the optic geometry which is determined by the boundary conditions of the theoretical treatment of this problem, as well as the repetition rate. This model presents an alternative approach to the "defect" model for thermal laser damage which focuses on the absorption of individual tiny impurities. By considering the macroscopic nature of heat diffusion over a long period of time and accounting for the geometry of the beam it is found that thermal laser damage may be caused by a gradual build up of heat in some cases, not just damage due to an impurity absorbing a high proportion of energy froma single incident laser pulse.

It is a success of this theory that it agrees with pulse duration and wavelength scaling laws. It also suggests a very significant dependence of LIDT on the beam and optic geometries. This has implications for laser damage diameter scaling and LIDT testing. The LIDT is predicted to be lower when the entirety of an optical surface is covered by the beam compared to small spot testing but differs from the square law[12] that is used on occasion. Realistically a component will be used in conjunction with beams of comparable size outside of a performance testing environment, the theory suggests that such testing may not be very representative of thermal laser damage behaviour out in the field.

The LIDT is in addition found to be highly dependent on the repetition rate of an incident pulse train if the repetition rate is comparable to or much greater than the cooling rate. If the repetition rate is significant in comparison to the rate of cooling then relations such as (3) and (4) can be used to predict the LIDT. Otherwise a single pulse model or the given maximum critical fluence F_* shall suffice.

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