Laser-induced Damage Threshold (LIDT) in Optical Components

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What is Laser-induced Damage ?

- Laser-induced Damage (LID) is damage caused to an optical coating or substrate when irradiated by a Laser.
- As early as 1962 McClung and Hellwarth (‘Giant Optical Pulsation from Ruby’) reported that ‘output light burned holes in the silvered surfaces’ of their ruby rod.
- Since then, the power available from Laser has increased substantially and we are now regularly dealing with Petawatt lasers!

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The Basics

- The Laser-induced Damage Threshold (LIDT) of optical materials is determined mainly by the following:
  - Beam size (the more power is concentrated in one spot the more likely the damage)
  - The Beam shape (Gauss / Supergauss – this will be examined in more detail later)
  - The Beam quality (hot-spots)
  - The coating / substrate materials (metals vs. dielectrics, coating and substrate quality)
  - The environment (cleanroom vs. dusty environment)

LID in common substrate materials

- Commonly used optical substrate materials incur LID due to the following
  - Dielectric breakdown (Fused Silica, Diamond, Quartz, Sapphire)
  - Thermal absorption ($LiNbO_3$, BK7)

Material	**LIDT @ 1064nm in J/cm^2**
Fused Silica	1.1×10^7
Sapphire (Al_2O_3)	7×10^6
Diamond	6×10^7
$LiNbO_3$	5×10^4
BK7	4×10^5

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LID in optical coatings

- Metal coatings predominantly damage as a result of thermal absorption
- Dielectric coatings generally show much lower absorption than metal coatings and defect-induced damage is more common.
  - Defects can be inclusions (dust particles)
  - The substrate surface can encourage irregular growth of coating layers, leading to defects
  - The coating parameters (deposition rate etc.) influence the quality of the coating.

How to scale LIDT

Ü For any given LIDT (LIDT(t_1)) at a pulse duration t_1, the approximate LIDT (LIDT(t_2) at pulse duration t_2 is given by

$$\mathrm{LIDT}\ (t_2) = \mathrm{LIDT}\ (t_1) * (t_2/t_1)^{1/2}$$

Ü **This rule works for pulse durations of approx. 1ns – 20ns.**

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Coating designs for high LIDT requirements

Ü In general, optical coatings made of ‘single stacks’, i.e. stacks of high- and low index coating materials of lambda/4 optical thickness, display the highest LIDT.

Ü The choice of optical coating materials (and the deposition parameters) are important.

What changes for Ultrafast Pulses?

Ü Mero et al (Phys Rev B71, 115109) have undertaken fundamental work to estimate the LIDT (critical fluence) of a material as a function of the pulse duration and material band gap. For Formula see next slide.

Ü Interestingly, they could not establish any relationship between LIDT and defects or impurities due to the manufacturing process. (confirmed by Stolz et al.)

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What changes for Ultrafast Pulses?

$$F_{th}= (C_1+ C_2E_g)\tau_p^{\ \kappa}$$

F_{th}: critical fluence

E_g: material band gap

τ_p: pulse duration

κ: material specific constant

c_1: empirical factor, -0.16+/-0.02 J/cm^{2}fs$^{-\kappa}$

c_2: empirical factor, 0.074+/-0.004 J/cm^{2}fs$^{-\kappa}$eV^{-1}

Coatings for ultrafast applications

Material	n_{800} (refractive index at 800nm)	E_0 (band gap energy)	κ	Theoretical critical fluence in J/cm2 for 15fs pulse
TiO_2	2.39	3.3 eV	0.28+/-0.02	0.18
Ta_2O_5	2.17	3.8 eV	0.33+/-0.02	0.30
HfO_2	2.09	5.1 eV	0.30+/-0.01	0.49
Al_2O_3	1.65	6.5 eV	0.27+/-0.01	0.67
SiO_2	1.5	8.3 eV	0.33+/-0.01	1.11

Source: Mero et al, Phys. Rev. B71, 115109 (2005)

What changes for Ultrafast Pulses?

- More recent work by Mangote et al (Optics Letters 37,9 1478, May 2012) looked into the relationship between the material’s refractive index and its LIDT
- Unfortunately, data was compiled for a 500fs pulse at 1030nm
- The empirical law they found is:

$$\mathrm{LIDT} = 12/n^2\ \mathrm{J/cm^2}$$

What changes for Ultrafast Pulses?

Ü While the authors are unable to give a scientific explanation for this equation it highlights a significant implication for coating design.

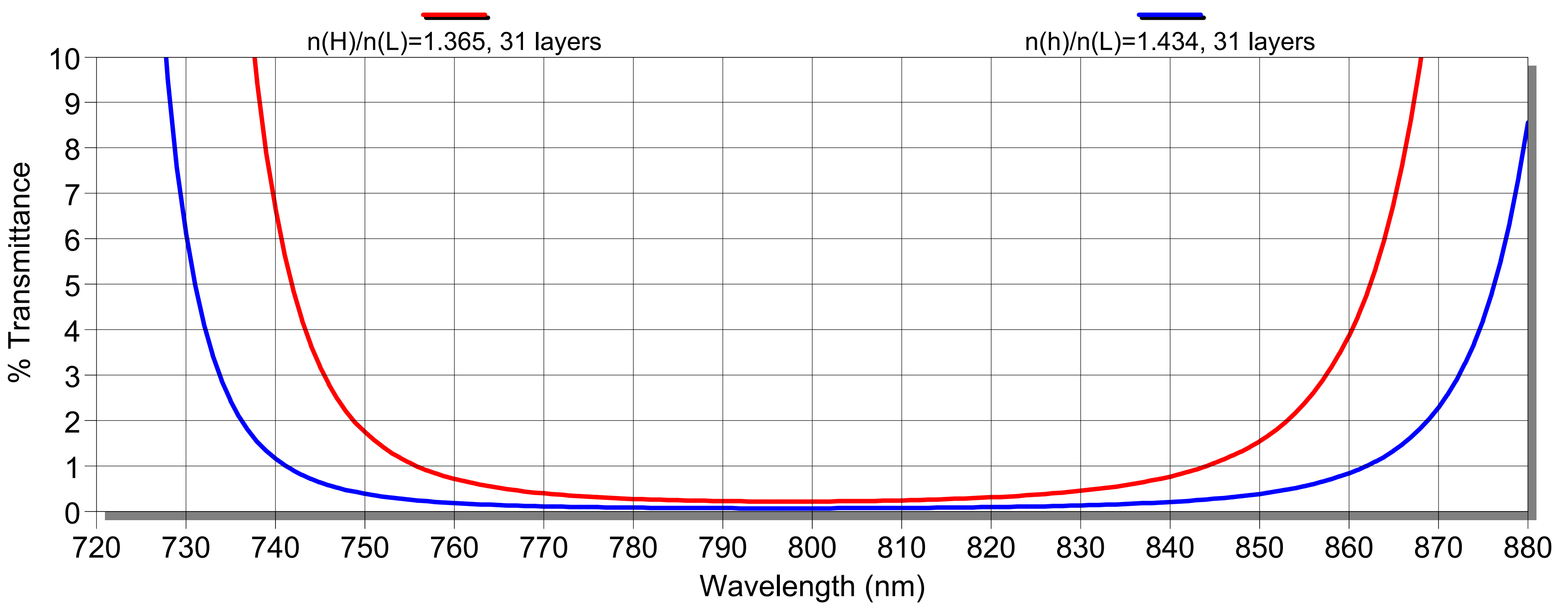
Ü The LIDT appears to decrease by a power of two with increasing refractive index !!!

Coatings for ultrafast applications

- Ü ‘Single Stack’ coatings display a high LIDT and good Group Delay Dispersion (GDD).
- Ü Spectral breadth is limited by ratio of refractive index between the 2 coating materials.
- Ü ‘Natural’ limit on achievable breadth.

Coatings for ultrafast applications

Performance shown under AOI of 45deg , p-POL



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Coatings for ultrafast applications

- Stack 1 (n(H)/n(L)=1.365) is compatible with high power
- Stack 2 (n(H)/n(L)=1.434) can only handle medium to low power
- Bandwidth of at least 750-850nm is required by most customers
- What can be done?

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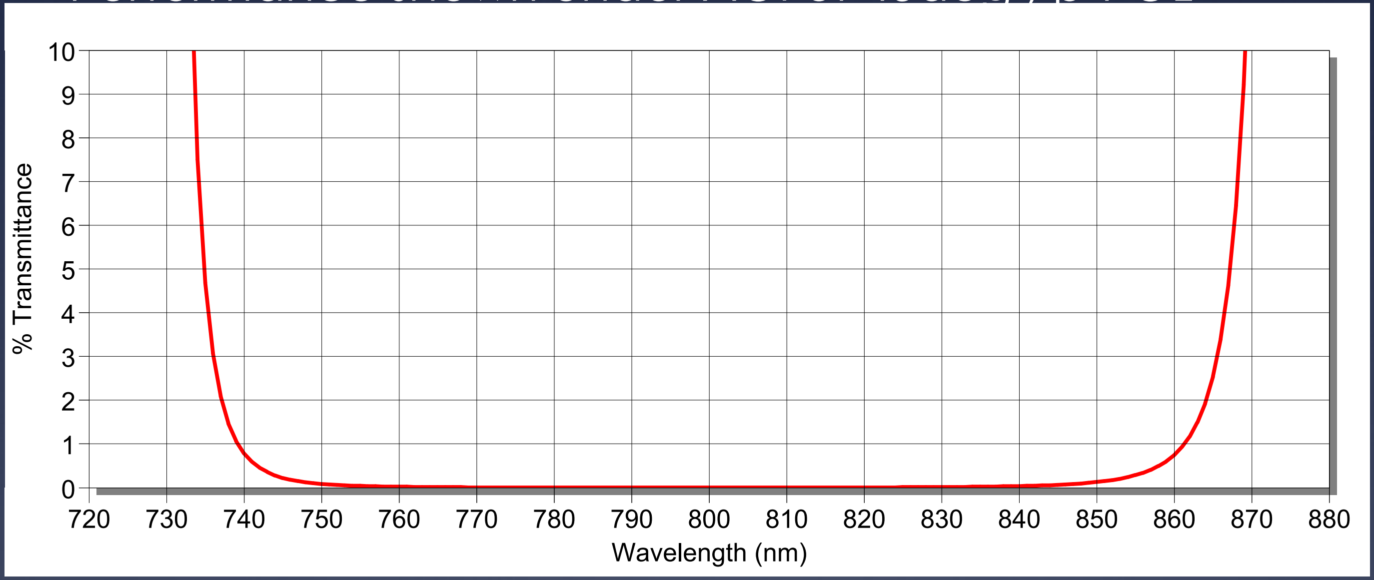
Coatings for ultrafast applications

- Solution 1: Combination of both stacks

Performance shown under AOI of 45deg , p-POL

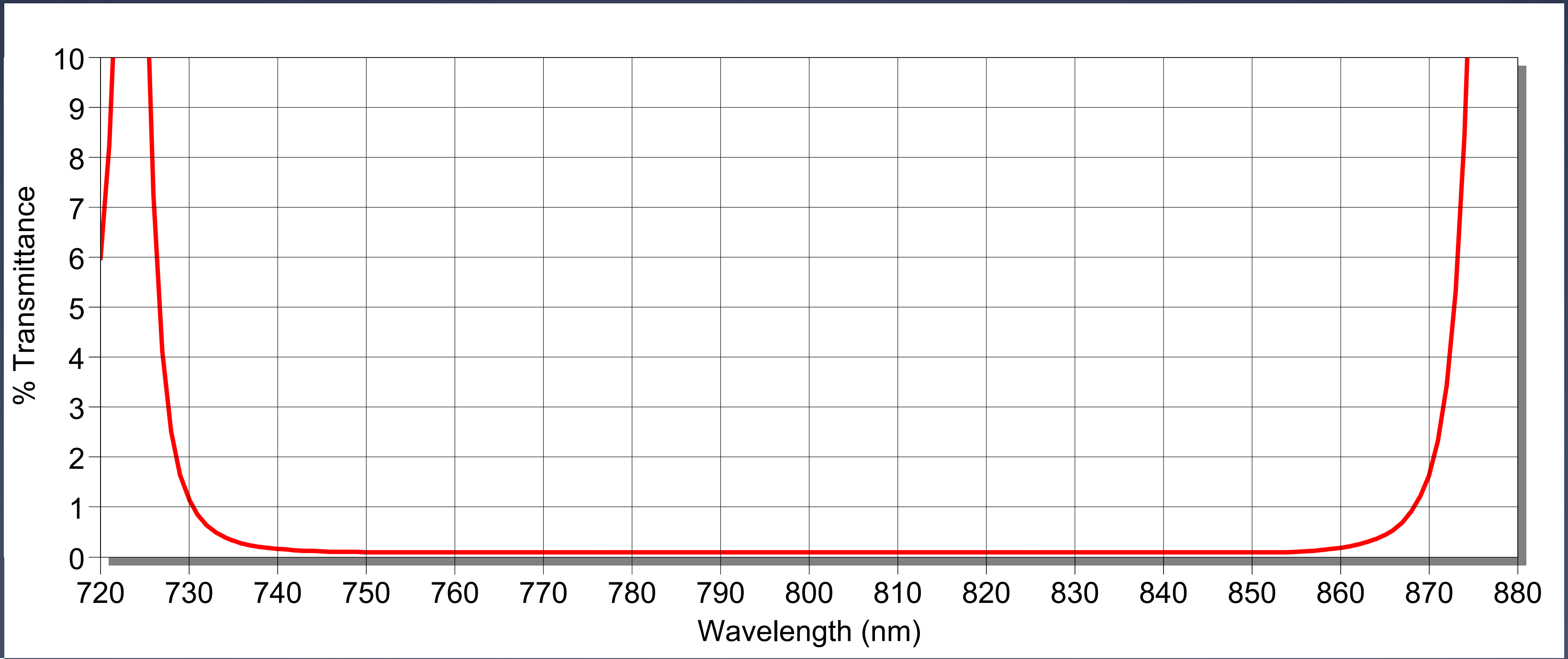


- **Good and easy solution, BUT:**
  - **Potentially problematic under vacuum (stress can cause crazing of the coating, especially for larger substrates**
  - **Design can cause spikes in GDD**
  - **Cannot handle spectral Supergauss beamprofiles well (Low LIDT)**

Coatings for ultrafast applications

Ü MPO’s solution – optimised design

Ü High LIDT, vacuum compatible (even for large substrates), low GDD, can be tailored to customer requirements.



Performance shown under AOI of 45deg , p-POL

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Any Questions ?