Laser Damage Testing for Ion Beam Sputtered Coatings at 2 µm and 3 µm

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The 2-3 µm spectral region is experiencing rapid growth due to the emergence of many important applications[1], as well as the continued development of a wide variety of appropriate laser materials. Some example applications are:

- 2 µm: Coherent CO_2 lidar for space, optical pumping of other laser materials and Optical Parametric Oscillators (OPOs), medical diagnostics, materials processing, and spectroscopy.
- 2-3 µm: Broadband tunable laser spectroscopy, materials processing, free-space laser communications, trace gas sensing (atmospheric, industrial, semiconductor), environmentally durable coatings[2] for intelligence/surveillance/reconnaissance windows and domes (scratch resistance, water resistance, sand/erosion, etc.), medical diagnostics
- 3 µm: (especially 2.94 µm, 2.8 µm) Erbium doped lasers are of special interest as this wavelength corresponds to the maximum level of water absorption[3,4]: laser scalpel/laser surgery, dentistry, dermatology; Material Processing: textiles, plastics, polymers; Infrared Countermeasures (IRCM).

The number and variety of laser materials in the 2-3 µm spectral region is growing as fast as the applications. Example materials are the 'traditional' mid-infrared solid state crystals: Ho:YAG, Tm:YAG, Ho:Tm:YAG, Er:YAG. There are also new or less standard Erbium-doped materials such as Er:YSGG, Er:Y_2O_3 [5], Er:ZBLAN fiber[6]. Several Chromium-doped chalcogenides[7] cover virtually the entire 2-3 µm region: Cr:ZnSe and Cr:ZnS. Established 1µm sources are used to pump OPOs with output wavelengths in this range, and a host of new fiber lasers are available. Finally, there are edge-emitting diode lasers as stand-alone sources or as pump sources for all of the above, Optically-Pumped Semiconductor Lasers[8] (OPSELs), and other novel semiconductor lasers[9].

Pursuit of these applications requires lasers that are very robust and reliable in the field or work site. This is the primary reason behind the rapid engineering developments for these laser sources over the past few years. Robustness for the optical coatings plays a key role in the overall reliability of these systems, and is a strong motivator for the use of Ion Beam Sputtered (IBS) coatings. Section 2 gives a brief background on IBS coatings, and Section 3 presents data for pulsed LDT at 2 µm. Section 4 describes 2 µm photothermal absorption measurements, Section 5 discusses 3 µm pulsed LDT data, and Section 6 gives a brief look at CW performance over the 2-3 µm range.

ION BEAM SPUTTERED COATINGS

IBS thin films are known for ultra-low absorption, near bulk density, Å-level surface micro-roughness ("conformal"), high LDT, and high environmental stability for a wide variety of film chemistries and wavelength ranges[10-13]. IBS provides the highest quality oxides in the visible to NIR regime (300 nm to ~2000 nm), using materials such as Ta_2O_5, SiO_2, TiO_2, HfO_2, and Al_2O_3. The higher deposition energy, compared to thermal evaporative techniques, provides essentially bulk packing density, low scatter, and insensitivity to absorption of chemicals such as water or other contaminants. The process is extremely well controlled, allowing deposition of hundreds of thin film layers with full computer control.

The near-UV through near-infrared is considered the typical range for these coatings, providing some of the highest LDT values in the industry. For example, Advanced Thin Films produces 1064 nm High Reflector coatings with damage thresholds of 48 Joules/cm^2 (for 20 nS pulses at 20 Hz, ~industry standard test conditions). The high transparency region for these and other materials extends well past the near-infrared, however, making them suitable for coatings at 2 µm and longer. While this is generally known within the optical coating community, there is nevertheless a lack of data that quantitatively details this extended range of high power IBS coating performance. This is one reason why optical designers have historically chosen lower performing electron beam evaporated coatings in this region.

One way to quantify coating material performance is to measure the transparency over a wide spectral range. While this is generally useful and a good starting point, it is not always a good indicator that the material will be suitable for high LDT coatings. So, this work instead concentrates directly on LDT data, and coating absorption at the parts-per-million level, for the 2-3 µm spectral range.

The transparency window mentioned above is also critical for the substrates onto which coatings are deposited. In addition to the majority of laser materials mentioned above (including fibers), other substrates suitable for high power IBS coatings in the 2-3 µm region are: infrasil, suprasil, undoped YAG, sapphire, silicon, silicon carbide, and germanium. Coating adhesion is extremely good, and several Advanced Thin Films-coated optics with 2 µm AR coatings operate at cryogenic temperatures.

2 µm PULSED LASER DAMAGE THRESHOLD

The first example involves a specific coating at 2 µm, and the most appropriate damage test involves a coating that transmits some or all of the light. This is because it is generally accepted that Anti-Reflective (AR) coatings have lower LDT than High Reflector (HR) coatings. Another factor that plays into LDT is the number of layers in the coating. A simple AR coating has relatively few layers, so a more robust damage test involves a coating with many more layers such as a non-Brewster angle Thin Film Polarizer (TFP). The measured spectral performance for such a coating is shown in Figure 1. Due to the longer wavelength, it should be noted that the overall coating thickness for this device is essentially twice that for the comparable optic at 1 µm. The curves in Figure 1 indicate the coating performance for both p-polarized and s-polarized light. For this device, the operating wavelength is 2.05 µm, and the polarization extinction ratio is about 1000:1. To avoid any substrate absorption effects and substrate defect issues, the coating was deposited onto infrasil that was polished in-house at Advanced Thin Films. The optic was tested for LDT at Spica Technologies, at the operating wavelength of 2.05 µm with a 100 ns pulse width, 25 kHz repetition rate, p-polarization (transmission), and 23 µm spot size. The part was irradiated up to 32.5 J/cm^2, with no observable damage in 20 sites. The outstanding performance of this relatively complex coating is a good indicator of the capability for IBS coatings at 2 µm.

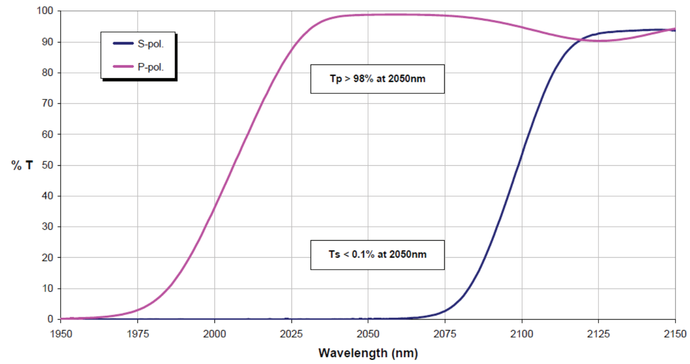

Figure 1. Measured coating performance for a 2.05 µm 45° Thin Film Polarizer, deposited onto a Advanced Thin Film-polished infrasil substrate. The lower limit for the measured damage threshold is >32.5 J/cm^2 (100 ns, 25 kHz). The optic was not damaged at all during testing, so the LDT exceeds the capability of the test laser.

The next test for the coating in Figure 1 was to evaluate the fundamental absorption in the coating. Recently, these types of precision absorption measurements have become more widely available due to the commercialization of Photothermal Common-path Interferometry, or PCI[14]. However, it is still very uncommon for these measurements to be performed in the 2-3 µm spectral region. Typically, the high power pump laser used for the measurement has a wavelength around 1µm, where the majority of very high power coatings are produced and high power CW lasers are readily available.

There is no fundamental reason why the PCI system must operate at 1µm, and in fact we were able to use a system with a 2µm pump laser, at Stanford University. The measured data for the coating of Figure 1 is shown in Figure 2 below. The details of this photothermal response curve as a function of axial distance from the coating plane are described elsewhere[14]. For the purposes of this paper, it is sufficient to point out that the measured absorption for the coated surface is 11.2 ppm. This is an extremely low value for a transmitting coating, and would generally be considered to be very good for a 1µm coating or a high finesse mirror. While pure absorption is not always a good indicator of whether a coating will have a high pulsed LDT, it is very representative of the performance for a CW situation.

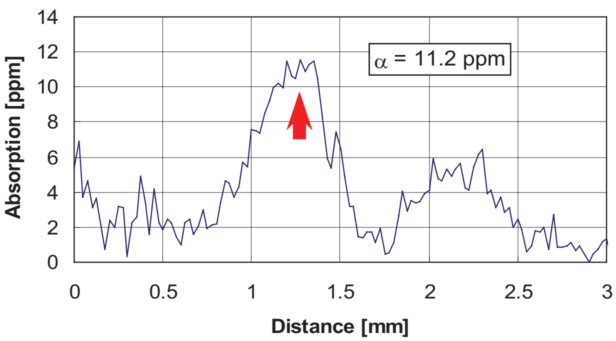

Figure 2. PCI Absorption measurement for the polarizer coating of Figure 1. The pump laser wavelength was 2.004 μm, and the absorption of the coated surface is only 11.2 ppm. The scan shows the absorption as a function of axial distance away from the coated surface, which is identified with an arrow.

3 μm PULSED LASER DAMAGE THRESHOLD

IBS coatings have a clear advantage in the 3 μm region, as their high density makes them completely impervious to water absorption. This is in stark contrast to the quite porous evaporated coatings that routinely absorb/desorb water, making both their spectral features and stress sensitive to humidity. Water has a maximum absorption around 3 μm, which makes it useful for numerous medical applications but simultaneously provides a challenge for high LDT optical coatings.

Our first example IBS coating around 3 μm is a 0° mirror designed for extremely high reflectivity (>99.99%) at 2.8 μm, using a suprasil 3000 substrate. This coating was tested at IPG Photonics using an Er:YSGG laser operating at 2.78 μm with 32 ns pulse width, 7 Hz repetition rate, and a Gaussian laser profile as shown in Figure 3. Testing results indicate that the LDT is >10J/cm^2, limited by the available pulse energy for the Er:YSGG laser. Once again, this represents a very good result, showing a 2.8μm pulsed LDT comparable to that achieved with coatings in the 1μm region.

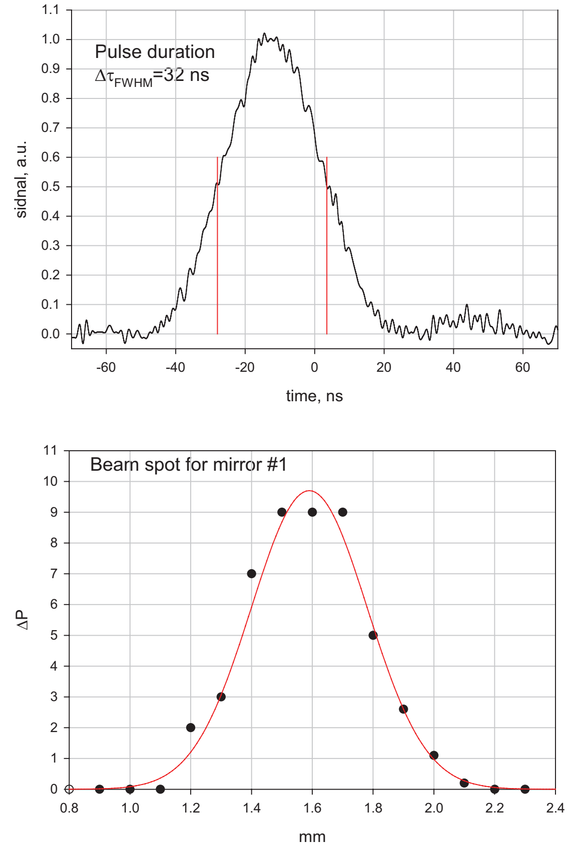

Figure 3. (top) Measured temporal profile of the Er:YSGG laser used for LDT testing of a 99.99% mirror at 2.8 μm. (bottom) Measured spatial profile.

The second IBS coating tested in the 3 μm region involved a coating for 2.94 μm, designed as a 45° HR for an Er:YAG laser, with a transmission band from 635-655 nm for an alignment laser. This is a relatively standard coating for Er:YAG lasers operating at 2.94 μm, and used single crystal sapphire as the substrate. The measured spectral trace for this coating is shown in Figure 4.

The medical industry is one of the biggest users of Er:YAG lasers, and it is often preferred to have a 'long pulse' output rather than a Q-switched output (Figure 5). This means that the lasers are operating with pulse widths of a few hundred microseconds rather than tens of nanoseconds. So, the corresponding peak power density is lower, but the integrated pulse energy is quite high. Testing of the mirror in Figure 4 under these conditions indicates a pulsed LDT of 1500 J/cm^2, 10 Hz, 100-on-1 test, ISO 11254 procedure. While comparison of the nanosecond LDT data and the microsecond LDT data is not clear-cut, this is considered an excellent result, especially in conjunction with the inherent insensitivity to humidity.

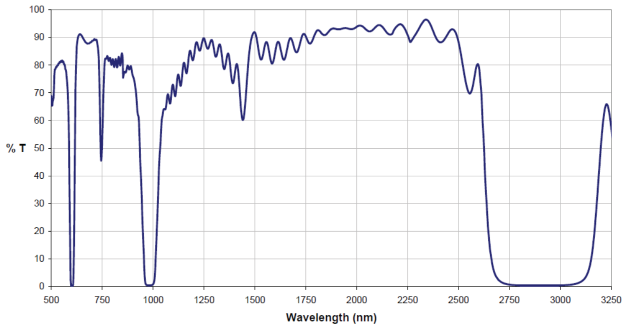

Figure 4. Measured IBS coating performance for a 2.94 μm 45° High Reflector, with partial transmission from 635-655 nm, deposited on a sapphire substrate.

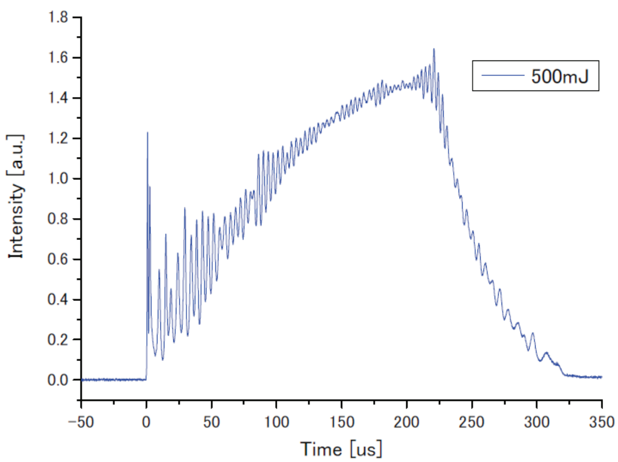

Figure 5. An example temporal pulse shape for an Er:YAG laser operating in the 'long-pulse' regime. The temporal profile is generally not as smooth as a Q-switched pulse and the peak power is lower, but the integrated energy per pulse is much higher. This pulse shape is more representative of the conditions for the dental and dermatology industries.

The final relevant category of testing is the continuous wave (CW) regime, and as with some of the other tests it can be challenging to obtain a laser that has sufficient power for estimating LDT. However, due to the lack of available data in this region, even placing limits on the LDT is useful. For this test, the 99.99% HR mirror at 2.8 μm was used, in conjunction with a CW tunable Cr:ZnSe laser. Table 1 shows the results, at several wavelengths within the Cr:ZnSe tuning range. In each case, the optic was not damaged, and the maximum laser power density was reached.

Wavelength	Estimated LDT, limited by CW Power Density
2.4 μm	> 767 kW/cm^2
2.5 μm	> 212 kW/cm^2
2.6 μm	> 170 kW/cm^2
2.7 μm	> 133 kW/cm^2

Table 1. Lower limit for the LDT under CW operating conditions. In each case, the maximum available power for the Cr:ZnSe laser was reached, without any observable damage.

SUMMARY AND ACKNOWLEDGMENTS

The data presented in this paper indicate that IBS coatings will likely become the performance leader for high power optics in the 2-3 μm spectral region, similar to the position they hold in the near-UV to near infrared. Much more data is still to be obtained, but the preliminary results show generally very high LDT values and very low absorption. These two characteristics ensure successful coating developments for a wide variety of high power optics. Future testing may involve detailed absorption measurements at 3 μm, further pulsed LDT testing for a variety of coatings, evaluation of high power 2 μm coatings on optical fiber, and extension of high power IBS coatings further into the infrared.

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