TECHNICAL PAPER

Materials and Processes for 1064nm Mirrors with High LIDT

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Materion Coating Materials News

Introduction

Coating processes and materials that increase the Laser Induced Damage Thresholds (LIDT) of coated surfaces have been discussed frequently in Coating Materials News [1]. The field is active with the latest research reported at the Laser Damage Symposium, a periodic international gathering of laser specialists for more than 50 years.

Many types of lasing media have been developed whose coated surfaces require durability and stability to the laser high energies that might be delivered as continuous irradiation (CW) or short pulses of very high energy density. The varying nature of damage created in the coating are functions of the peak energy, pulse width, spot area and repetition rate. CW exposure produces localized heating, resulting in melting and stress-induced cracking. Short pulses damage by ionizing the surface to produce a plasma that further erodes and vaporizes the coating. A common source for initiating damage is the presence of defects in the coating that might take the form of µm-sized inclusions from the deposition process, or other physical defects such as scratches and pits residuals of polishing/cleaning procedures. Absorption due to impurities contained in or on the surface of coated layers is also a source of failure, especially in the UV wavelengths [2, 3, 4].

Common Laser Sources

The Nd:YAG laser with fundamental wavelength at 1064 nm is used in many high-powered applications. It has received the most attention relative to LIDT applications. Coatings including high reflectors, anti-reflection, beam-dividers, polarizers, and filters on a variety of substrate materials are subjected to laser power densities as high as 250 W/cm^2 CW and 100 J/cm^2 for nano-second to femto-sec pulses. Surviving these energies and powers for various applications and environments challenges the state of the technology to increase LIDT development. Even with the rise of diode and fiber lasers where the fundamental wavelength can be further tuned for the application, the burden falls on coating technology at the most crucial surfaces during generation, delivery, and utilization of the beam.

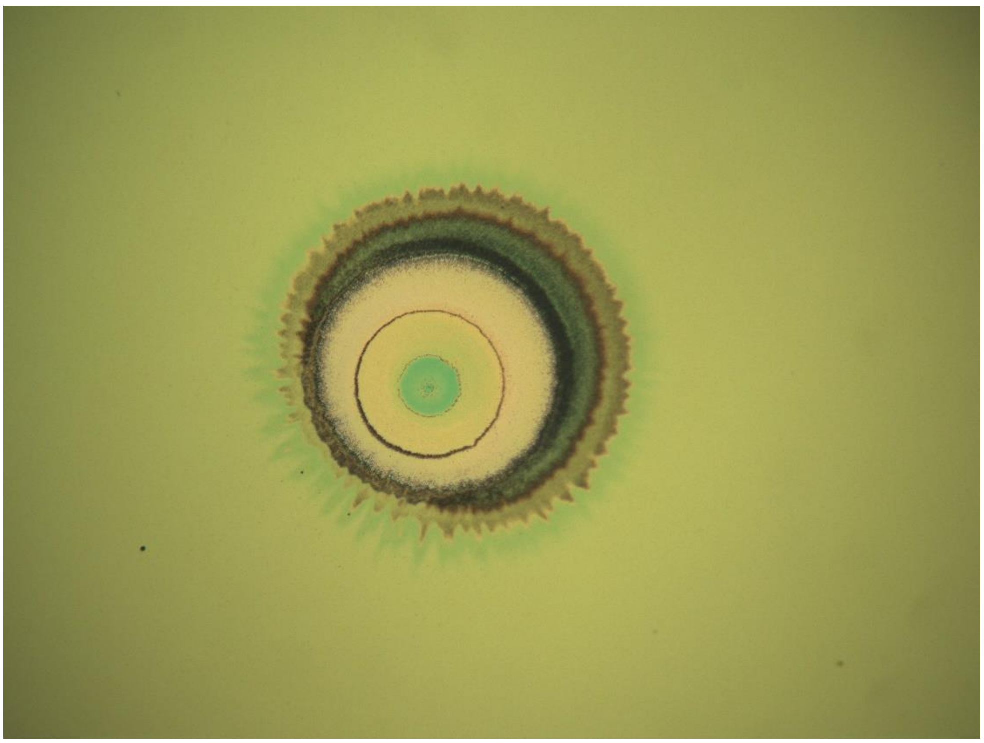
The availability of different wavelengths from Nd:YAG lasers satisfies several application needs. The second, third, and fourth harmonic wavelengths at 532 nm, 355 nm, and 266 nm, respectively, are used for visible and UV applications including medical, communication, and power generation. Resonances are generated by second or third harmonic non-linear generation in crystals. Multi-layer frequency multiplier mirrors (for UV) using specific coating designs optimize efficiencies in selected wavelengths.

1064 nm wavelength is used in military range finders at low powers, and in the machining and marking of metals and plastics at moderate to high power densities. Ophthalmology uses IR and Visible lines for refractive correction and disease surgeries. Soft dental tissues can be treated or excised. In cosmetic applications, tattoos can be removed. And in medicine, cancers and other lesions can be ablated with less collateral damage to adjacent tissues. LIDAR systems employ lasers for distance calculation in applications for autonomous vehicle control and remote topographical mapping. International ignition facilities operate at petawatt powers to generate energy from fusion product.

A similar lasing material is YAG with fundamental wavelength 1053 nm and its higher harmonic wavelengths. 1053 nm and 1064 nm are not eye-safe wavelengths. Glass lasers at 1550 nm are eye safe and are used in consumer applications where exposure is not a threat.

Damage Testing and Evaluation

The values quoted for the LIDT of a coating depend on the test methodology. The LIDT test used is dependent on the application of the High-reflector (HR) mirror. Large-aperture optics with large beams and low repetition rates versus applications involving a small-beam at high repetition rates. Different procedures include single shot at a single location (N on 1), multiple shots on a single site (S on 1), and most commonly, ramping the fluence on a single site until damage is detected (ISO test). Because damage initiation sites are distributed in size and location, raster scanning is more appropriate for large area exposure to produce a statistical average of the LIDT probability, which is the highest fluence where damage is first detected. The two tests give different LIDT values (higher with the ISO test protocol using 100:1 shots), but the same behavior relative to the most to least resistant coating sample. The 2019 Laser Damage Symposium retested the 2018 samples using the raster scan method covering a 1 cm^1 area.



Defect Driven Damage as seen on Samples From Laser Damage Competition.
Image Source: [Spica Technologies Inc.]

As a surface is disrupted by the laser energy, damage onset can be visualized with Nomarski microscopy or recorded as increase in scatter [1]. Laser resistance is often specified in terms of power density, W/cm^2. In the case of pulsed irradiation where the pulse width can be measured as the FWHM of a focused test beam, spot 1/e^2 diameters are ~1 mm. Pulse widths can vary from nano-second to femto-second depending on the laser. The power density at the coated surface is computed from the energy per pulse in Joules/cm^2. Nano-sec pulsed energy delivered in a 1 mm

Materials and Deposition Processes

For the purpose of reporting on the progress being made by various commercial coating companies that provide laser-resistant coated optics, an international competition is held at the Boulder damage symposia. Contestants must meet the requirements for a high reflector at 1064 nm with 99.5% reflectance at 0 deg incidence. Participants chose materials, design, cleaning, and deposition process. Exposure involved pulses of 3 ns width, 5 Hz repetition rate, 1/e^2 beam diameter 950 µm single-shot exposure [2, 3].

High-reflector mirror (HR) designs are based on QW layer thicknesses. The low index materials included MgF_2 and SiO_2 (with some attempts using Al_2O_3). High-index materials included HfO_2, Ta_2O_5 and ZrO_2. Damage vulnerability is higher in the high-index layers, and therefore the development of processes and materials was focused on the high-index components. The deposition processes included e-beam, e-beam IAD, IBS and PIAD. Substrate preparation is also a critical ingredient for achieving high LIDT. Different cleaning methods included plasma etching, solvent hand- or ultrasonic- cleaning.

Results of the Competition

The 2008, 2018 and 2019 Laser Damage Symposium competition results for 1064 nm Nd:YAG coatings were consistent. The highest LIDTs were obtained with coatings deposited by e-beam using HfO_2 and SiO_2. This combination with plasma etching cleaning produces the fewest defects or damage initiators (of size ≤10 µm) per unit area. The lowest performers were those containing Ta_2O_5 and ZrO_2. HfO_2 reactively evaporated from Hf metal emits far fewer particulates that can be damage initiators than does evaporation from the oxide compound [5]. The same cause for low LIDT is blamed on a high population of particulate defects present with other high-index materials. The best results are LIDTs 82 J/cm2 tested by raster scanning and 100 J/cm2 tested by ISO standard test ('No damage' criteria) for HfO_2 / SiO_2 reflectors [3]. This material and deposition process combination for 1064 nm lasers also gives the highest LIDT at the UV 3rd harmonic 355 nm wavelength.

Concluding Comments

Studies and many recent publications indicate that deposition process is as important as the correct material combination to achieve high LIDT and low scatter. The primary sources of low LIDT are coating µm-sized particulates that become damage sites. Success requires the absence or very low surface density of particulates and inclusions, even as small as 5 – 10 µm. Depending on wavelength (IR to UV), power density, pulse width, and repetition rate, damage can also be initiated by contamination, absorbed water, and internal defects. Layer morphology plays a role in this complex matrix of failure mechanisms. Amorphous dense layers are more resistant than crystalline layers that can have lattice displacement and porosity. High-energy deposition processes such as sputtering produce dense amorphous morphology, often resulting in incomplete stoichiometry due to dissociation or vacancies. Alternatively, reactive e-beam deposition produces layers free of chemical dissociation and can be porous unless low energy IAD is added. E-beam deposition is the most successful process for UV and longer wavelength high LIDT. The high-index component is chosen for large bandgap to avoid intrinsic absorption. Avoidance of particulate emanation is achieved using the metal and not the oxide compound as the starting material.

References

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