THERMAL EFFECTS ON MIRROR COATING INTEGRITY IN HIGH-POWER LASER SYSTEMS AND NUCLEAR APPLICATION

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SUMMARY: This study investigates how dielectric, silver, and gold mirror coatings respond to thermal stress from high-energy laser pulses, as observed through experimental interferometry and spectral analysis. Conducted at the Extreme Light Infrastructure - Nuclear Physics facility in Magurele, Romania, this research explored deformation, stress behavior, and optical resilience in real-world laser interactions. Dielectric coatings showed minimal expansion and deformation, maintaining optical integrity, while silver and gold absorbed more energy and experienced notable thermal distortion. These findings support the use of dielectric mirrors in extreme photonic environments such as industrial laser processing and nuclear research.

KEYWORDS: mirrors, lasers. thermal stress, dielectric materials, strength

2. Introduction

In the world of high-power photonics, mirrors are no longer passive components. They are precision-engineered, multilayered interfaces responsible for controlling and guiding some of the most intense energy fluxes produced by humanity. From ultrafast laser systems to advanced industrial applications, mirrors are tasked with reflecting beams that can burn through steel, initiate nuclear reactions, or trigger femtosecond-scale diagnostics. Yet these mirrors remain vulnerable to their own function. When faced with high fluence and rapid thermal cycling, even a nanometer defect or distortion can spiral into catastrophic failure. As laser powers increase into the petawatt range, understanding how different mirror coatings behave under thermal stress becomes essential not just for system performance, but for the survival of the optical elements themselves. This research investigates three widely used coating materials (dielectric stacks [1], silver, and gold) under thermal stress generated by high-energy laser pulses. By coupling experimental fringe analysis with thermal modeling and spectral diagnostics, we quantify how each coating type reacts, deforms, and potentially fails. Our goal is to identify which materials are most thermally robust, and what trade-offs exist in choosing coatings.

3. Scientific background

Mirror coatings represent the interface between optical precision and material science. When subjected to high-power laser beams, they undergo thermal phenomena governed by physical parameters such as: absorption of energy, leading to localized heating; thermal expansion, disorting surface geometry; stress gradients from uneven heating, risking deformation or delamination.

Dielectric coatings (typically multilayer stacks of $SiO2$ and $TiO2$ or $Ta2O5$) are engineered for minimal absorption and precise spectral control but require complex thermal management. Silver offers superior reflectivity in the visible range but tends to overheat due to absorption in the near-infrared. Gold performs better thermally than silver in the infrared spectrum, though its density and moderate absorption limit its use under extreme laser fluences.

4. Experimental setup – Mach-Zehnder interferometer

The investigation combined optical interferometry to assess deformation and energy absorption.
The Mach-Zehnder interferometer splits a coherent laser beam into two optical paths: one serving as reference, and the other directed onto the test mirror [2]. Upon recombination, any phase distortion caused

by surface deformation leads to fringe pattern shifts. These fringe distortions serve as direct indicators of thermally induced stress and optical surface expansion.

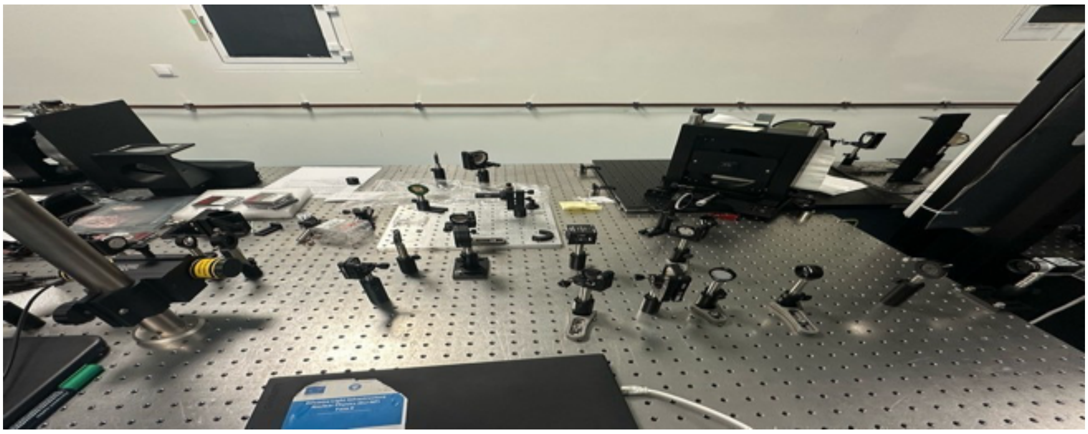

Fig. 1. Interferometer setup in the Optics Laboratory, Magurele

The interferometric system was built using four high-reflectivity planar mirrors, two precision beam splitters (BS1 and BS2), a set of collimating lenses for spatial coherence, a high- resolution Basler camera paired with Pylon software [3], the laser source and the analysed mirror with the specific coating.

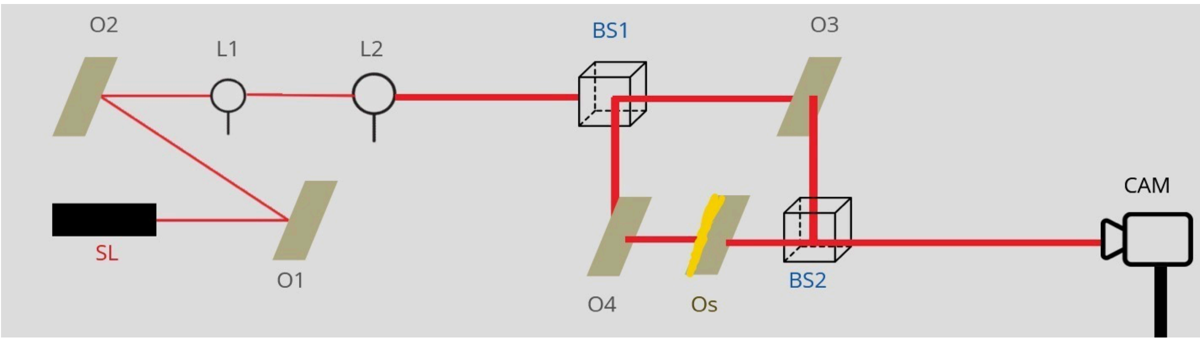

Fig. 2. Schematic of the interferometer

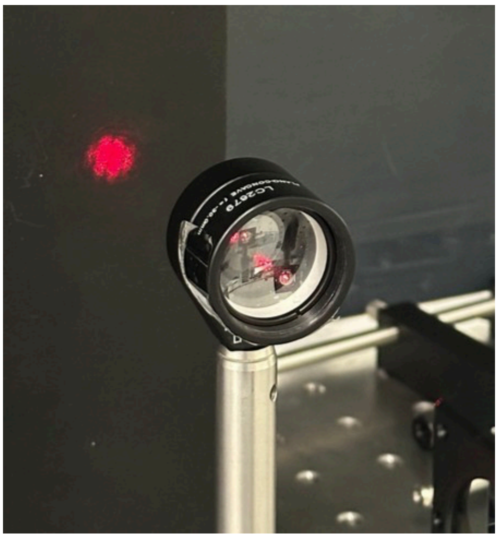

Fig. 3. Fringes seen with the naked eye

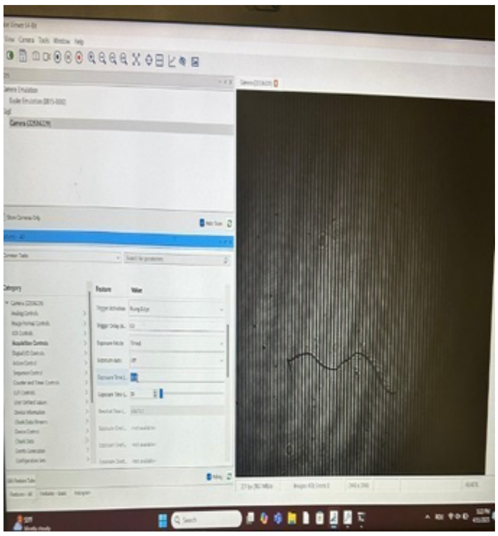

Fig. 4. Pylon software

4. **Group delay dispersion evaluation**

To better understand the phase integrity and temporal behavior of laser pulses interacting with optical coatings, a detailed analysis of **Group Delay Dispersion (GDD)** was conducted for each mirror type. GDD is a second-order dispersion parameter defined as the derivative of the group delay with respect to angular frequency or wavelength [4]. In essence, it quantifies how much different spectral components of a pulse travel at different speeds through a material or are reflected with different phase delays. This becomes especially critical in femtosecond laser systems, where even slight phase mismatches across the spectrum can stretch a pulse temporally, introduce chirping, or reduce the peak intensity upon focusing.

The dielectric mirror exhibited a controlled GDD curve, indicating minimal distortion introduced during broadband reflection. This performance is a result of the mirror's carefully engineered multilayer stack, typically alternating layers of high- and low-index materials (e.g., Ta_2O_5 and SiO_2) designed to achieve both high reflectance and controlled phase response. In practice, the measured GDD for this mirror stayed well below ±100 fs² across the 700–900 nm interval, which is within acceptable limits for pulse durations below 30 fs. This makes the dielectric coating the most suitable candidate for chirp-free propagation in ultrafast beamlines, particularly when maintaining Fourier-limited pulse duration is necessary for precision interactions with matter.

In contrast, the silver-coated mirror displayed erratic GDD behavior, with measured values fluctuating rapidly and exceeding ±400 fs² at multiple wavelengths. These oscillations are caused by the intrinsic material properties of silver, which lacks the dispersion-engineered structure of dielectric stacks. The result is a spectral phase profile that severely alters the time structure of any femtosecond pulse, potentially increasing the duration by an order of magnitude and weakening the fluence at the focus. For this reason, despite its excellent reflectance in the visible range, silver coatings are generally unsuitable for use in front-end compressors or ultrafast diagnostics where phase linearity is critical.

The gold-coated mirror offered a more stable, though still moderate GDD performance. Its GDD curve featured a smoother profile than silver's, with a broad peak near 720–740 nm followed by a gradual descent toward the infrared. While values were not as low or flat as those observed in the dielectric case, they remained within ±200 fs² over most of the spectrum. This makes gold a viable option for applications involving longer pulses (e.g., >100 fs), mid-IR wavelengths, or situations where thermal durability outweighs the need for strict dispersion control.

Quantifying GDD is vital not only for characterizing temporal fidelity, but also for predicting cumulative effects when multiple optical elements are involved. In high-power laser systems like those operated at ELI-NP, even a small phase error introduced at each bounce can accumulate over beam paths of tens of meters, distorting temporal pulse structure and reducing system efficiency.

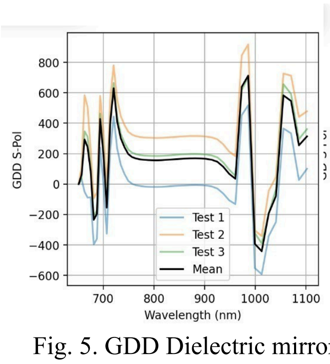

Fig. 5. GDD Dielectric mirror

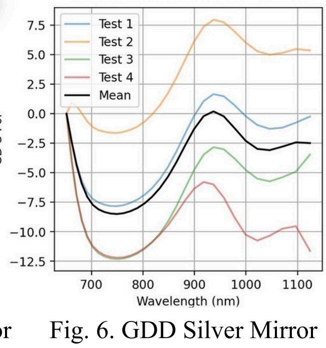

Fig. 6. GDD Silver Mirror

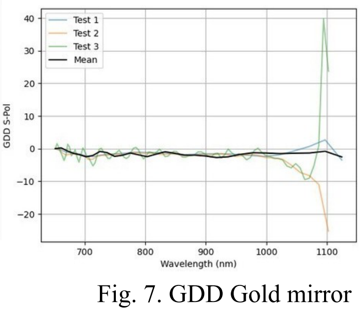

Fig. 7. GDD Gold mirror

5. Finite element analysis

To complement the interferometric and GDD evaluations, finite element analysis (FEA) and heatmap visualization in MATLAB were performed on all three mirror types to estimate thermal stress, energy absorption, and surface deformation under simulated laser exposure. The dielectric-coated mirror showed a uniform, low-intensity absorption profile. Despite the appearance of red regions in the heatmap, the absorbed energy never exceeded ~0.0027 J/cm², well below its damage threshold. The mirror maintained energy stability across the surface, highlighting its suitability for ultrafast optics.

The gold-coated mirror revealed central energy concentration between 0.15–0.5 J/cm², forming concentric rings likely caused by local roughness or interference. Absorption exceeded the damage threshold (~0.1 J/cm²), indicating higher risk of localized thermal failure. Despite excellent IR reflectance, gold's density and absorption require strict thermal management. Silver-coated mirrors exhibited the highest and most uneven absorption— ranging from 0.3 to 0.8 J/cm², significantly surpassing their known damage threshold (~0.225 J/cm²). The presence of concentric high-intensity zones aligned with micro-defect interference suggests a combination of poor phase stability and local absorption spikes. These behaviors reinforce previous observations from GDD and fringe deformation.

To explain these results at the atomic level, we must consider the microstructure and crystal arrangement of each coating material. Dielectric coatings are typically composed of alternating layers of non-metallic oxides, such as SiO_2 and Ta_2O_5. These materials are amorphous or polycrystalline and do not contain free electrons, which minimizes both absorption and conduction of heat. Their structure is tightly bonded, with wide band gaps that prevent significant energy uptake from incident photons, contributing to the uniform heatmap observed.

In contrast, both silver and gold are metals with a face-centered cubic (FCC) lattice structure. This crystal arrangement allows for high packing density and malleability but also results in a high density of free electrons in the conduction band. When exposed to intense laser light, these free electrons absorb and re-emit energy, causing localized heating. The increased electron mobility facilitates non-radiative energy transfer, which elevates temperature gradients in small regions.

Silver, in particular, has a relatively low melting point and surface hardness, making it more susceptible to deformation and damage when microstructural imperfections—such as dislocations or surface roughness—enhance localized absorption. Gold is slightly more thermally stable but still shares the same FCC structure and free-electron behavior [5], which explains the concentric thermal absorption rings and higher central intensities.

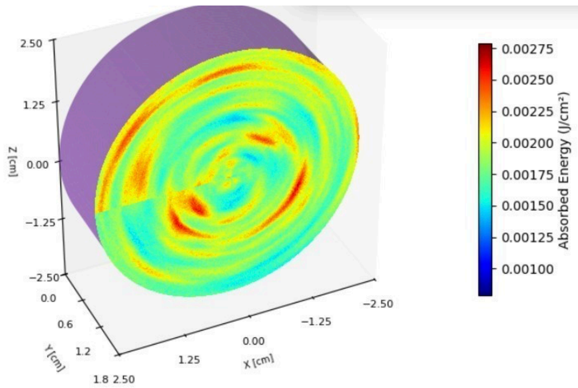

Fig. 8. Dielectric mirror heatmap

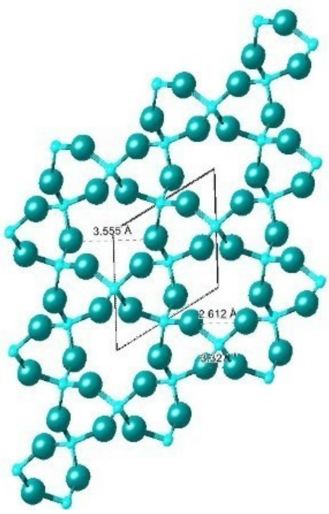

Fig. 9. SiO2 base structure

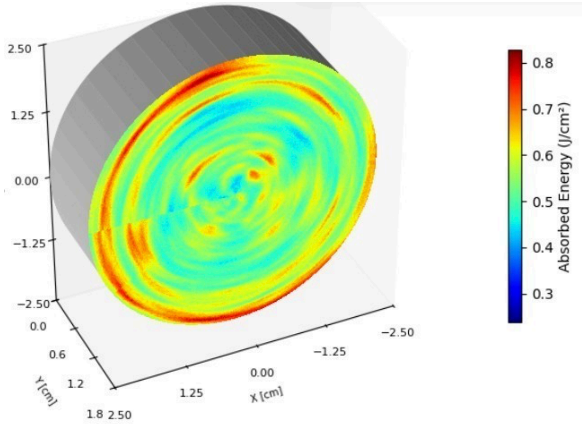

Fig. 10. Silver mirror heatmap

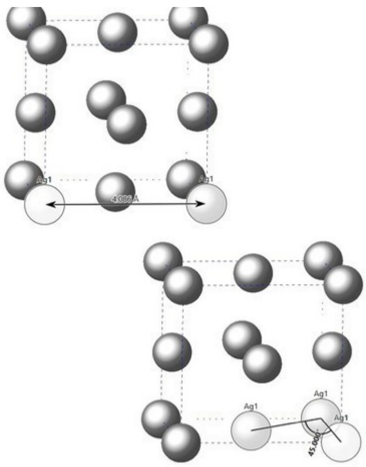

Fig. 11. Ag atomic structure

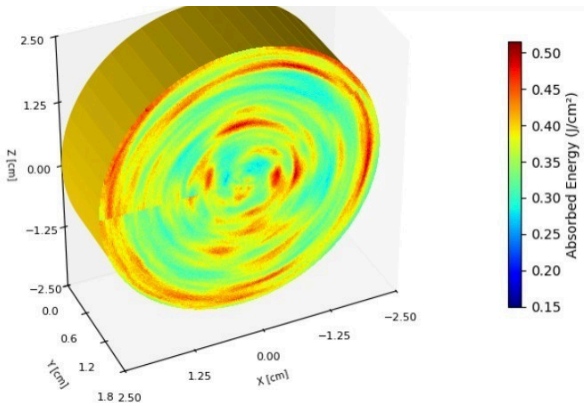

Fig. 12. Gold mirror heatmap

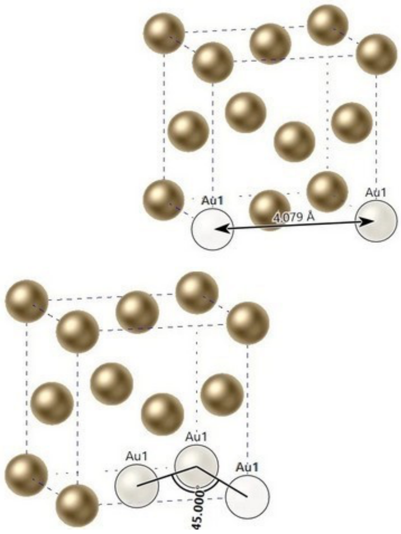

Fig. 13. Au atomic structure

6. **Conclusions**

Dielectric-coated mirrors show the highest thermal and optical stability under high-power laser exposure, with minimal deformation and low absorption.

Although the manufacturing of dielectric stacks can be more demanding due to layer precision and angular sensitivity, their benefits in long-term stability, damage threshold, and spectral control far outweigh these challenges. Their performance under femtosecond-scale fluences confirms their superiority in environments where thermal resilience and optical coherence are critical.

The increasing complexity of high-power laser systems demands optical components that can withstand extreme thermal and mechanical stress while maintaining phase stability. This study highlights how material structure, electronic properties, and coating design influence mirror performance under such conditions. By combining experimental data with simulation and atomic- scale analysis, we gain insight into the mechanisms behind deformation and energy absorption, paving the way for future innovations in photonic materials and thermal-resistant coatings.

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