Electric-Field Enhancement Caused by Subwavelength-Sized Particles Located on the Surface of Multilayer Dielectric Mirrors

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An important factor that limits the output performance of laser systems is the coupling of energy from the laser beam into localized areas of its constituent optical components, which leads to permanent modification of the affected localized regions (commonly referred to as laser-induced damage). There are a number of underlying mechanisms that introduce such localized damage precursors that are typically associated with the introduction of impurities during the manufacturing process, during handling and installation of the optic, or due to contamination during operation. While this problem has been extensively investigated for large-aperture nanosecond laser systems, the impact of particle contamination on the laser-damage performance of short-pulse laser systems has only recently received attention.[1,2] Whereas most of the optics of concern in nanosecond laser systems are transmissive, optical elements for short-pulse laser systems are typically reflective and are based on metal or multilayer dielectric (MLD) coating designs. A laser pulse impinging on the surface of an optical component can interact with particles, such as contamination debris, to produce a scattered electric field. The coherent superposition of this scattered field with the incident laser field can significantly increase the local field intensity. This effect can be of critical importance because it can reduce the laser-induced–damage threshold of the affected component. To address this issue, a combination of experimental and modeling effort is required to assess the specific features of such contamination particles that pose a high risk for the lifetime and performance of the optics. These features include the size of the particles in combination with their shape and their optical and thermomechanical properties.

In this work, we use a field-propagation code to determine the magnitude and location of the electric-field enhancement arising from the presence of small particles located on the surface of MLD mirrors. In our modeling we consider a steady-state, monochromatic electric-field distribution within the volume of interest. Taking into account the 20 to 30 fs required for fields to propagate throughout the simulated volume, the results are directly applicable to laser pulse durations longer than that time. For shorter pulses, we would need to consider the time-dependent nature of the electric-field distribution. The monochromatic nature of the simulations also neglects potential effects due to broad bandwidths of ultrashort pulses. Here we study the following variables:

- Particle material: transparent dielectric or metal with high reflectivity
- Particle size $\lambda/8$ to 2λ (for laser wavelength λ)
- Particle shape: regular (spherical, cubic, triangular) or irregular
- Region of interest: particle surface, inside the particle, and inside the coating
- Particle density: coherent effects arising from adjacent particles

The model estimates the peak electric-field intensity as a function of the particle size normalized by the incident wavelength. Two particle shapes (rectangle and triangle) and two classes of material optical properties (dielectric/transparent and metal/absorbing) are considered. Figure 1 summarizes the modeling results providing the maximum field intensity values and their general location separated into four general categories: inside the MLD layers, inside the particles, below the surface of the optic (within the MLD layers), and on the surface of the particle. The shape and material optical properties of the particle (such as the reflectance by the particle surface and its absorption properties) govern this interaction. Furthermore, the locations and value of

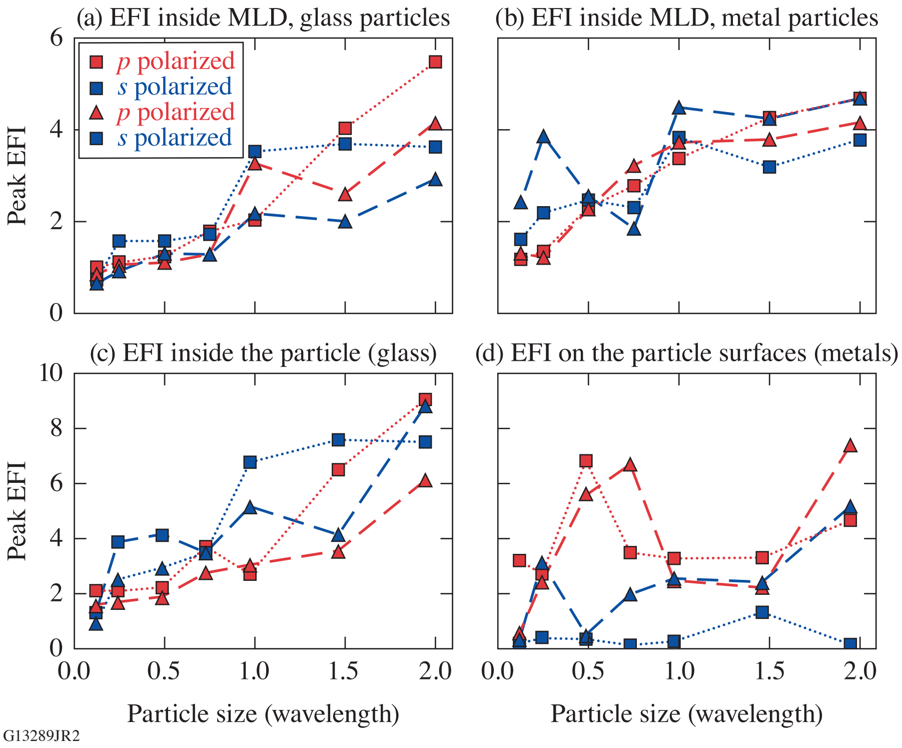

Figure 1
The peak electric-field intensity (EFI) as a function of the ratio between the particle size and the incident wavelength for two particle shapes (rectangle and triangle depicted as solid squares and triangles, respectively) using *p*-polarized and *s*-polarized (red and blue shapes, respectively) laser beams inside the MLD for (a) glass and (b) metal particles, (c) inside the bulk for glass, and (d) on the surface for metal particles.

maximum field intensity are indicators of the locations of damage initiation and the corresponding reduction of the laser-damage threshold in the presence of debris particles, respectively.

The results suggest that particle sizes as small as 1/4 of the laser wavelength can introduce a field enhancement that is higher than that inherent to the coating-design parameters. Such particles would be very difficult to detect after the installation of the optic; therefore, an effective way for detecting particles smaller than wavelength may be needed. Understanding the field enhancement on laser optics caused by contamination particles located on the surface is important in terms of estimating the associated reduction of the laser-induced–damage threshold. On the other hand, understanding of the field enhancement on the particles help understand secondary contamination effects[1,2] that can also have detrimental effect on the damage resistance of the optic. Although this study is limited by the resolution and the nature of the 2-D modeling, we expect that the general conclusions are still valid. We plan further studies using more advanced modeling capabilities to further study specific cases that are relevant to the performance and lifetime of optics located inside the grating compressor chamber in the OMEGA EP Laser System. Quantitative modeling of this effect provides guidance to determine quality control for fabrication, handling, and maintenance of optics.

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