MIRRORS AND WINDOWS FOR HIGH-ENERGY LASERS:
THE WAVEFRONT DISTORTION PROBLEM

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ABSTRACT

High-energy laser (HEL) systems involve an optical train consisting of mirrors and windows, which may compromise the system's operation because of unavoidable wavefront distortions resulting from the absorption of some fraction of the incident laser-beam energy. The first part of the paper concerns actively cooled HEL reflectors; a generalized mirror/heat-exchanger model is used for evaluating both irradiance-mapping and coolant-pressure induced distortions. The theory of thermal lensing of HEL windows is reviewed in part 2; the purpose is to clarify the role of stress-induced birefringence effects and to apply the figure-of-merit concept to key laser-window material candidates.

INTRODUCTION

The development of high-energy laser (HEL) systems has stimulated a great deal of activity relating to the physics and the technology of optical components designed for handling high-power beams of infrared light. The reason for this is that typical HEL systems involve an optical train, which must be capable of transporting and directing the laser beam without seriously degrading the nominal performance of the system. Available experience indicates that catastrophic failure modes associated with thermally induced stresses or temperature excursions are not a major threat. The performance of the system, as measured in terms of achievable target irradiances, initially degrades on account of "thermal lensing," that is, the process of beam defocusing and beam distorting caused by thermally generated phase aberrations. Since HEL operation usually requires close-to-diffraction
limited characteristics at the far-field focus, this lensing phenomenon must be carefully assessed in relation to specific features of the optical train. In this paper, I will summarize analytical investigations of relevance in evaluating how laser-driven mirror/window distortions may affect the performance of HEL systems; specifically, I will provide simple expressions for judging the relative merits of both mirror-substrate materials and window-material candidates with regard to enhancing the focal intensity.

In the absence of birefringence, the far-field intensity derives from the Huygens-Fresnel integral and amounts to

\[ I_{GF} = \left( \frac{k}{R_0} \right)^2 \left| \int_0^{D/2} E(\rho) \exp[i \delta \phi(\rho, t)] \rho d\rho \right|^2 \]  

at the Gaussian focus, on assuming cylindrical geometry. The phase-aberration function \( \delta \phi \) maps the cumulative aberrations impressed on the beam while propagating through the optical system and relates to the optical path difference (OPD) simply by means of the propagation constant. For weak distortions, we may proceed by expanding \( \exp(i \delta \phi) \) to second order, which leads to a highly compact expression:

\[ I_{GF} = \kappa_0 \left\{ 1 - k^2 \text{var}[\text{OPD}] \right\} \]  

if the variance is defined in accord with \( \text{var}[X] = \langle X^2 \rangle - \langle X \rangle^2 \), the brackets symbolizing amplitude-weighted averages. Note that \( \kappa_0 \) represents a beam-profile factor and accounts for the possibility that non-uniform beam intensities may cause some reduction in far-field irradiance, even in the absence of near-field phase aberrations. The degradation in focal intensity thus obeys a "Strehl-relation" type equation, which implies that the optical train should remain nearly diffraction-limited as long as the square root of the OPD variance does not exceed \( \lambda/14 \). Throughout the rest of this paper, we will rely on the magnitude of \( \text{var}[\text{OPD}] \) for assessing the loss in focal irradiance caused by the emergence of phase aberrations in the near field.

THE MIRROR PROBLEM

Currently operational beam-relay/beam-steering mirrors consist of a thin, highly reflecting faceplate, which transfers to a coolant fluid the fractional laser energy that is deposited at the surface, and which is stiffly held to a stable backup structure that minimizes thermomechanical deformation modes. Thermally induced surface deformations resulting from spatial variations in beam intensity generate "irradiance-mapping" wavefront distortions and have been the subject

* For a listing of the symbols, refer to the Appendix.