Neutron Irradiation Testing of Dielectric Mirrors for Inertial Fusion Energy

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Objective

The goal of this work is to accurately evaluate the changes in optical performance and mechanical durability of dielectric mirrors optimized for application in an ionizing and displacive irradiation environment.

Introduction

Laser Inertial Fusion Energy (IFE) offers an attractive approach to sustained fusion energy production. One area of technology critical to the long term operation of a laser fusion facility is the impact of irradiation effects on optical materials, particularly highly reflective laser mirrors. Multilayered dielectric mirrors could significantly improve transmission of reflected electromagnetic energy, but little is known about their longevity in a high dose level radiation environment. We are examining the survivability of high reflective dielectric coatings intended for use as either the final optic or next to final optic in a laser fusion power plant. We are specifically considering dielectrics that operate at the Krypton Fluoride Laser wavelength of 248 nm; but these should also be appropriate for 351 nm.

Background

Earlier work shows differing opinions as to the use of dielectric mirrors in fusion applications. A key issue is if changes in the substrate material offers increases in damage resistance.

E.H. Farnum *et al.* (1995)

Examined:

- HfO_2 / SiO_2, ZrO_2 / SiO_2, TiO_2 / SiO_2 mirrors on SiO_2 substrates.
- Neutron fluence: 10^{19} n/cm^2 , 270-300ºC.

Outcome:

- Fewer and thinner bi-layers improves resistance to environment effects.
- Excessive damage in HfO_2 / SiO_2 and ZrO_2 / SiO_2 mirrors, including flaking and crazing of films.
- SiO_2 substrates are not damage resistant; suggested use of more damage tolerant substrates (Al_2O_3 and $MgAl_2O_4$).

K. Vukolov (2005)

Examined:

- TiO_2 / SiO_2, ZrO_2 / SiO_2 mirrors on KS-4V silica glass.
- Neutron fluence: up to 10^{19} n/cm^2, 275 ºC.

Outcome:

- Fewer bi-layers in mirror improve thermal cycling properties.
- Dielectric mirrors were resistant to neutron irradiation up to tested fluence.

Radiation and Environment Issues

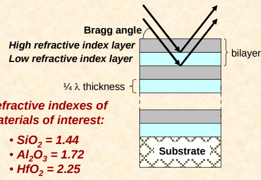
- Differences in radiation and thermally induced swelling or expansion between the alternating layers or layers and substrate.
- Radiation / thermally induced structural changes within a given layer.
- Radiation / thermally induced mixing or formation of interlayer compounds.
- Changes in reflectivity peak towards lower wavelengths.
- Changes in optical absorption due to radiation induced defects.

Dielectric Mirrors (background theory)

Coatings which allow the reflection of a specific wavelength, while blocking others. Composed of alternating multilayer films of high and low refractive index materials of quarter wavelength thickness.

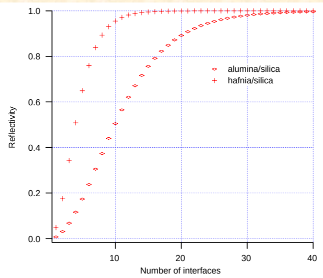
The reflectivity (R) of a lossless multilayer stack of N successive quarter wave layers of alternating high (n_{Hi}) and low (n_{Li}) refractive index.

$$R = \left(\frac{1-b}{1+b}\right)^2 \quad \textit{where} \quad b = \Pi_{i=0}^{N}\left[\frac{n_{Li}}{n_{Hi}}\right]$$



Refractive indexes of materials of interest:

- ***SiO_2 = 1.44***
- ***Al_2O_3 = 1.72***
- ***HfO_2 = 2.25***



Calculated reflectivity of two UV coatings vs number of interfaces (number of interfaces is equal to twice the number of layer pairs)

IFE Mirror Requirements

- Reflectivity: > 99.8% at 248 nm, (99.5% from 238 to 258 nm)
- Absorption: < 500 ppm measured at 248 nm
- Scattering: total integrated scattering < 500 ppm at 633 nm
- Laser Damage Threshold: ~10 J/cm^2 at 248 nm, 2 ns FWHM pulse
- Total neutron flux to mirror: ~1x10^{13} n/cm^2 s (first mirror) , ~1x10^{11} n/cm^2 s (final)

  Total neutron fluence in IFE in one year, assuming 80 % plant availability = 2.5x10^{18} n/cm^2 (final mirror) to 2.5x10^{20} n/cm^2 (first mirror)

- Total gamma dose rate to mirror: ~3x10^{12} p/cm^2 s (first mirror), ~6x10^{10} p/cm^2 s (final)

Experimental Approach

- Conduct testing on three mirror designs along with individual single layer coatings on Al_2O_3-sapphire substrates:

Sample / Description	Quantity
Al_2O_3-sapphire *substrate only*: 6 mm diam. x 1 mm thick	18
Single coating (same thickness as a layer in mirror) of Al_2O_3 on substrate	18
Single coating (same thickness as a layer in mirror) of HfO_2 on substrate	18
Single coating (same thickness as a layer in mirror) of SiO_2 on substrate	18
Dielectric mirror: Al_2O_3 / HfO_2 on substrate	18
Dielectric mirror: SiO_2 / Al_2O_3on substrate	18
Dielectric mirror: SiO_2 / HfO_2on substrate	18

- Deposition of films by electron-beam with ion-assist and/or ion beam sputtering.
- Irradiation at the High Flux Isotope Reactor at ORNL.
  - Three neutron fluences: 10^{18}, 10^{19} and 10^{20} n/cm^2 at 60 ºC.
  - Additional tests at 10^{19} n/cm^2 fluence at 300 and 500 ºC.
  - Three test samples per test condition including non-irradiated controls.
  - Non-irradiated controls also tested following thermal cycling.

Testing and Evaluation

- Samples tested before and after irradiation.
- Non-irradiated controls test before and after thermal cycling.
- Optical testing includes:
  - Visual inspection: scratch/dig, irregularities and color changes.
  - Reflectivity (mirrors only)
  - Transmission
  - Absorption
  - Reflected wave-front error.
  - Surface roughness
  - Film / coating thickness

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