FINAL OPTICS MODELING

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OUTLINE

- Objectives of final optics modeling
- GIMM surface defect types and modeling approaches
- Fresnel modeling of multi-layer films

  (1) Oxide-coated Al mirror
  (2) Contaminated mirror

- Ray tracing and wave scattering approaches
- Future plans

Modeling Objectives

- The GIMM (grazing incidence metal mirror) is subjected to damages from:

  (1) X-rays, (2) γ-rays, (3) neutrons, (4) laser radiation,
  (5) charged particles, and (6) debris.

- The primary objective for final optics modeling is to quantitatively analyze the effects of these damages on the quality of laser beam focusing on the target.

  A secondary objective is to more accurately define the design windows for the GIMM, such as power density threshold, protective coating, material selection, operational lifetime, than previously done.

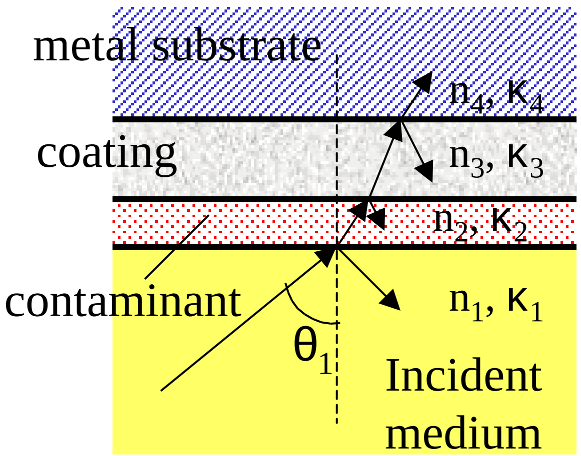
- Damages to the mirror can have three main effects:

  - Beam (on target) defocusing, and wavefront distortion
  - Increased beam absorption at the mirror
  - Shorter mirror lifetime

Mirror Defects and Damage Types, and Approaches to Assess Beam Quality Degradation

Dimensional Defects		Compositional Defects	
Gross deformations, $\delta > \lambda$	Surface morphology, $\delta < \lambda$	Gross surface contamination	Local contamination
CONCERNS			
• Fabrication quality • Neutron swelling • Thermal swelling • Gravity loads	• Laser-induced damage • Thermomechanical damage	• Transmutations • Bulk redeposition	• Aerosol, dust & debris
MODELLING TOOLS			
Optical design software	Potential scattering theory (perturbation analysis)	Fresnel equation solver	Potential scattering theory (perturbation analysis)

Fresnel Modeling of Reflectivity



- Wave propagation in four stratified layers of media is modeled. Surface is assumed to be smooth ($\delta << \lambda$). [Born & Wolf, Heavens]
- Each medium is homogeneous, with uniform thickness, and is characterized by complex refractive index: n = n (1 + i κ)
  n = (ε/μ)$^{1/2}$; κ = attenuation index
- TE (S) polarization is assumed.

- Refraction : $n_1 \sin \theta_1 = n_j \sin \theta_j$ j = 2,3,4 (Snell's Law)
- Reflection : $r_{i,i+1} = (n_i \cos \theta_i - n_{i+1} \cos \theta_{i+1}) / (n_i \cos \theta_i + n_{i+1} \cos \theta_{i+1})$ (Fresnel)
- Reflectivity is computed by repetitive usage of the 3-layer formula:

$$r_i = [r_{i-1,i} + r_{i+1} \exp(i2\beta_i)] / [1 + r_{i-1,i}\, r_{i+1} \exp(i2\beta_i)]$$

where $\beta_i = (2\pi/\lambda_o)\, d_i\, n_i \cos \theta_i$, i = 2,3 and d_i is the layer thickness, and

setting intensity reflectivity as $R = | r_2 |^2$.

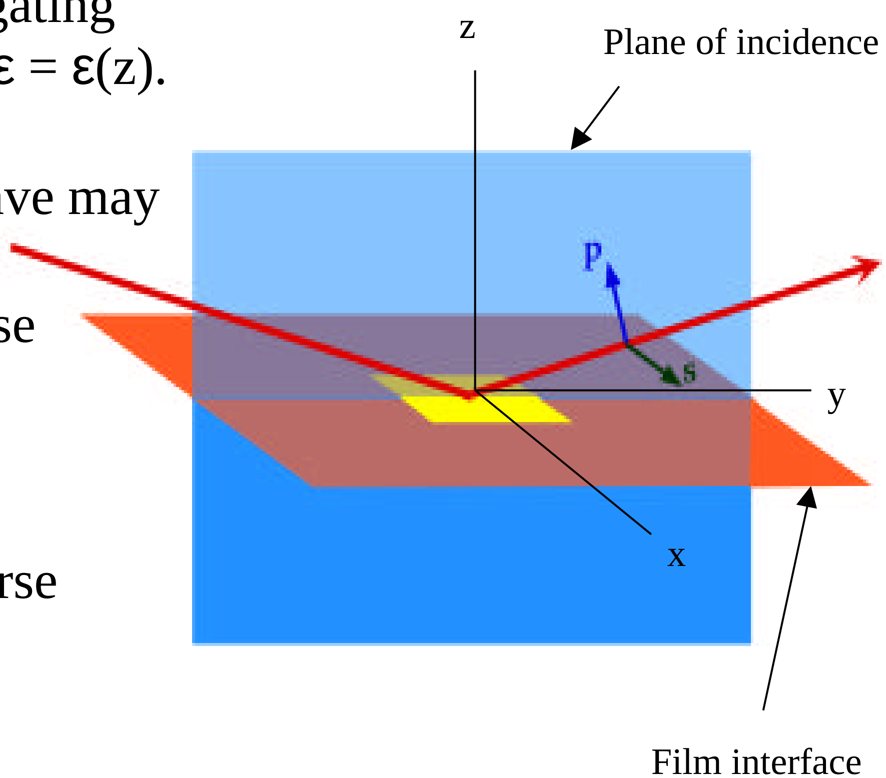
S- and P- Polarizations

- Consider a plane EM wave propagating through a stratified medium with $\varepsilon = \varepsilon(z)$.

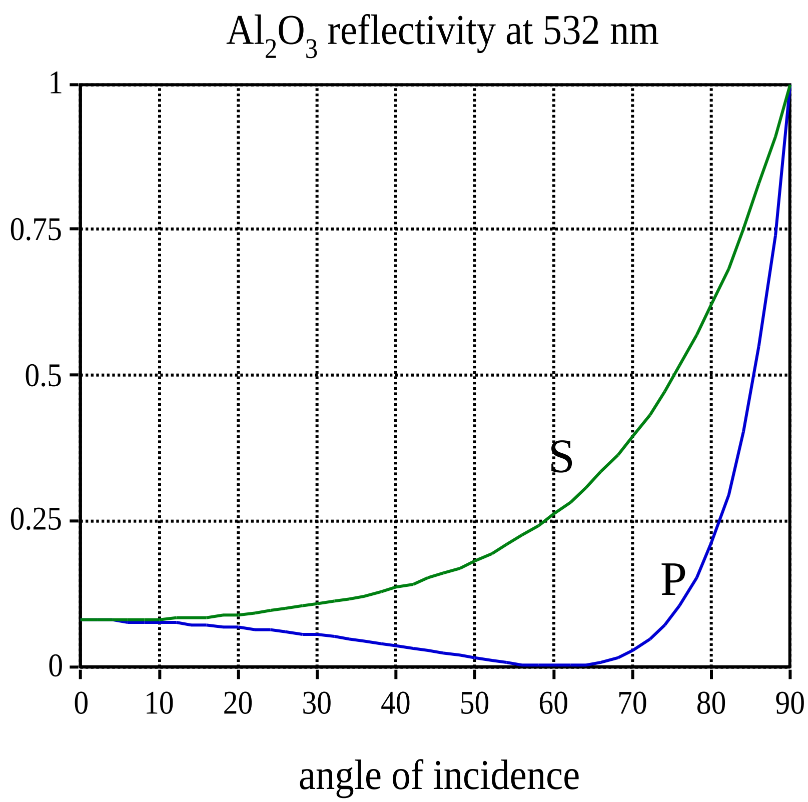
- Any arbitrarily polarized plane wave may be resolved into two waves:
  (1) TE (S) with $E_s = E_x$, transverse to plane of incidence, i.e., y-z plane
  $H = (H_y, H_z) = H_{||} = H_s$
  (2) TM (P) with $H_p = H_x$, transverse to plane of incidence
  $E = (E_y, E_z) = E_{||} = E_p$

- Thus, in vector form, $\underline{E}_{tot} = \underline{E}_s + \underline{E}_p$,

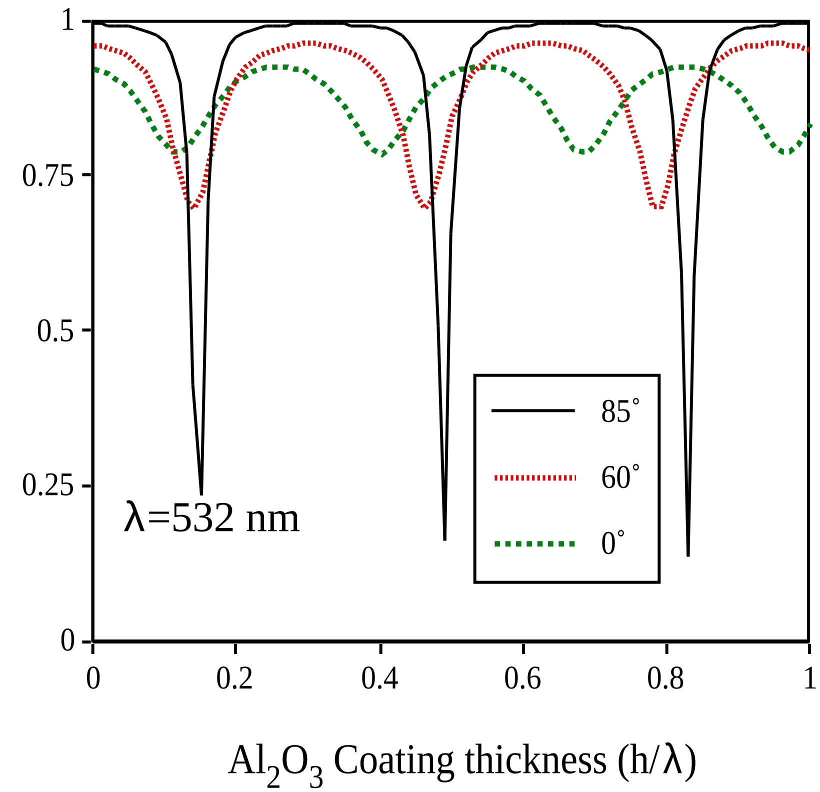
  as shown in the diagram.



Reflection of S-polarized (TE) waves including thin oxide coating



P-polarization undergoes total transmission at $\theta \sim 60^o$.

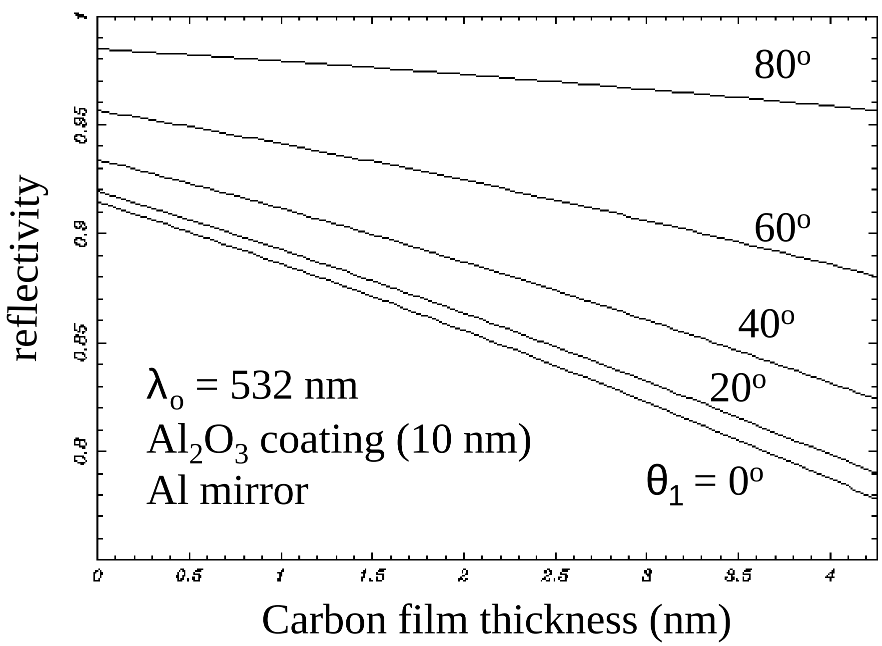


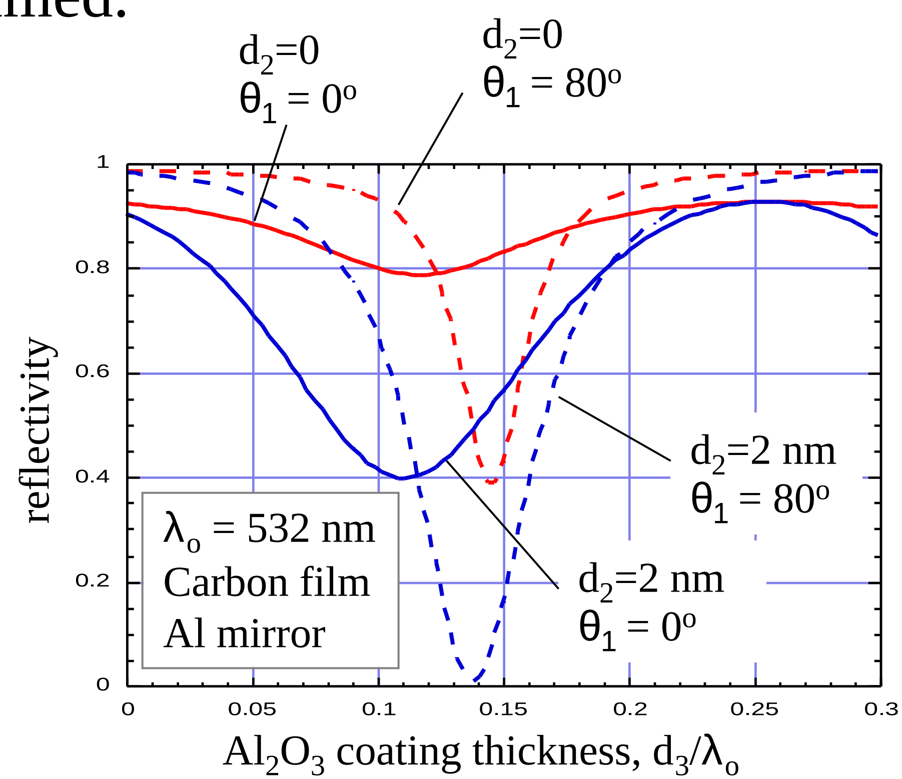
Periodic variation in *R* is due to interference effect in oxide coating.

Effect of surface contaminants

- Surface contaminants (such as carbon) on mirror protective coatings can substantially alter reflectivity, depending on layer thickness and incident angle.

- Uniform film thickness is assumed.





Ray Tracing and Optical Design Software

- When surface defect $\delta > \lambda$, effect on beam focusing can be assessed using the ray tracing approach.

- There are numerous optical design programs that perform ray tracing on all types of surfaces and media with complex refractive index.

- One such design package is ZEMAX-EE from Focus Software, Inc. Features include:
    - Complete polarization ray tracing and analysis capability (transmission, reflection, absorption, polarization state, etc)
    - Supports arbitrary user defined surfaces (shape, optical properties)
    - Extensive thin film modeling capability
    - Integrated tolerance analysis capability: RMS spot radius, RMS wavefront error, etc as criteria.
    - Nonlinear model of thermal effects on index of refraction and material expansion.

- Procurement of an optical design software package is being considered.

Wave Scattering from Rough Surfaces

- When surface roughness or deformation $\delta < \lambda$, part of incident wave is scattered off the specular direction in a diffuse manner, thus degrading the focusing of the beam on a target.

- Two analysis approaches:
  - Perturbation theory (Raleigh-Rice): valid for $\delta << \lambda$

    Expand $\psi^{sc} = \psi_0^{sc} + \psi_1^{sc} + \psi_2^{sc} + \ldots$ where $\psi_n^{sc} = \vartheta(\delta^n)$

    Surface roughness characterized by 2-D power spectral density:

    $$P(\vec{k}) = \lim_{A\to\infty} \left\langle \frac{1}{A} \left| \int_A d\vec{r} e^{i\vec{k}\cdot\vec{r}} \delta(\vec{r}) \right|^2 \right\rangle$$

  - Physical optics (Kirchoff): valid for $\delta < \lambda$

    Solve for total scattered field (coherent+diffuse), with approximation. For Gaussian δ distribution, overall scattered intensity is given by

    $\langle I \rangle = I_o e^{-g} + \langle I_d \rangle$, where g << 1 for slightly rough surfaces, and g >> 1 for very rough surfaces; I_o is energy scattered from smooth surface, and I_d is diffuse intensity.

- Perturbation approach is simpler; physical optics technique is valid over wider range of surface roughness.

SUMMARY & FUTURE PLANS

- Fresnel analysis of oxide-coated metal mirrors has been carried out using a 4-layer model and assuming smooth surfaces.
  - Surface contaminant can have impact on reflectivity.

- Investigation into effects of mirror defects and induced damages on beam focusing has just begun.
  Goal is to determine design windows for GIMM and other optical subsystems for ARIES/IFE studies by relating these damages to heat deposition and neutron fluence.

- Two approaches are being examined:
  (1) Ray tracing with vendor design software ($\delta > \lambda$)
  ZEMAX-EE is a candidate package.
  (2) Wave scattering approach ($\delta < \lambda$)
  Further study is required to identify appropriate method:
  Perturbation analysis or physical optics?
  * Examine if ZEMAX can be used for this purpose.
  * Search for wave scattering software in public domain.