Postprint: Broadband High-Reflectivity Coatings for 2.5 m Aperture Mirrors

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Date: 2025-04-08T16:02:35+00:00

Abstract

To enhance the observational capability of astronomical telescopes, the aperture of primary mirrors is continually increasing, while the requirements for their coatings have become more stringent, necessitating broader reflection bands and higher reflectivity. To meet the demands of domestic astronomical telescopes, a broadband high-reflectivity coating technology for large-aperture mirrors based on ion beam assisted deposition was developed. By analyzing the geometric configuration of the 3.2,m coating equipment and the linear energy distribution region of the ion source, a dual-ion-source zoned independent control approach was implemented, achieving coatings with excellent optical constant consistency across the 2.5,m aperture aspheric mirror surface. Starting from the actual surface figure of the 2.5,m primary mirror prior to coating, the mirror height during deposition was determined through simulation, and the shape and dimensions of the correction plate were calculated to ensure coating uniformity better than 1.2%. Following the design of the coating stack, test samples were positioned at various locations on simulated substrates for actual deposition; upon testing, each sample achieved the design targets. Based on these experimental results, employing ion beam assisted deposition technology and utilizing the 3.2,m coating equipment, the broadband high-reflectivity reflective coating for the 2.5,m primary mirror was successfully fabricated.

Full Text

Preamble

Vol. 66 No. 2
Mar., 2025

Acta Astronomica Sinica (天文学报)
doi: 10.15940/j.cnki.0001-5245.2025.02.005

Study on Wide-Spectrum High-Reflectivity Coatings for 2.5 m Aperture Mirrors

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Abstract

To improve the observational capabilities of astronomical telescopes, primary mirror apertures are continuously increasing, while coating requirements become more stringent, demanding both broader reflection bandwidths and higher reflectivity. In response to domestic astronomical telescope needs, this study investigates a wide-spectrum, high-reflectivity coating deposition technique for large-aperture mirrors using ion beam-assisted deposition (IBAD). By analyzing the geometric configuration of a 3.2-meter coating facility and the linear energy distribution region of the ion source, we employed a dual-ion-source partitioning method with independent control to achieve coatings with excellent optical constant consistency across a 2.5-meter aspheric mirror surface. Based on the actual surface figure of the 2.5 m primary mirror prior to coating, we determined the optimal mirror height during deposition through simulation and calculated the shape and dimensions of a correction plate to ensure coating uniformity better than 1.2%. After designing the multilayer coating system, test pieces were placed at various positions on a simulated substrate for actual deposition. Testing confirmed that each test piece met the design targets. Using these experimental results, we successfully completed the wide-spectrum high-reflectivity coating of the 2.5 m primary mirror using IBAD technology in the 3.2-meter coating facility.

Keywords: instrumentation: wide spectral and high reflective film, telescopes, techniques: spectroscopic, techniques: ion beam assisted deposition

1. Introduction

The size of a telescope' s primary mirror determines its system resolution—only larger aperture mirrors can achieve higher resolution. Large telescopes require mirrors with higher reflectivity. In large optical systems, light often undergoes multiple reflections, making the overall optical efficiency the product of the reflectivities of individual mirrors. Improving mirror reflectivity is therefore crucial for enhancing entire optical system efficiency. With advances in optical and photometric measurement technologies, the usable spectral range has expanded from visible light to a broad band covering ultraviolet through infrared, necessitating research into wide-spectrum reflective coatings. Consequently, developing wide-spectrum, high-reflectivity coatings for large optical components has become essential.

Currently, two primary deposition methods are used for large-aperture mirrors: thermal evaporation and magnetron sputtering. Magnetron sputtering offers controllable particle direction, allowing mirrors to be coated face-up, avoiding risks during flipping and hoisting. The high initial kinetic energy of deposited particles produces dense microstructures, a technique employed in telescopes such as Gemini and VLT (Very Large Telescope). However, the abundance of charged particles during sputtering can reduce film purity, and the technique has significant limitations in depositable material types.

Thermal evaporation operates in high vacuum, yielding high-purity films. However, conventional thermal evaporation of large mirrors typically uses face-up or vertical orientations to mitigate coating and hoisting risks, restricting evaporation to resistive heating and limiting material selection, film density, and adhesion. This approach has been used in LBT (Large Binocular Telescope), Subaru, MMT (Multiple Mirror Telescope), the Yunnan Astronomical Observatory 2.4 m telescope, and the NAOC 2.16 m telescope developed by Nanjing Institute of Astronomical Optics & Technology.

Ion beam-assisted deposition (IBAD), a form of thermal evaporation, operates in high vacuum. The ion source can etch the substrate before deposition to remove microscopic contaminants, improving film adhesion. During deposition, kinetic energy exchange from the ion source provides greater initial energy to coating molecules, increasing their mobility on the substrate and producing denser films. Ion bombardment also enhances film adhesion and density, increasing refractive index while reducing extinction coefficient. The face-down coating orientation facilitates electron gun operation, expanding the range of depositable materials. Due to these advantages, IBAD is commonly used for high-precision coatings on small-to-medium aperture optics, including LAMOST sub-mirrors, the Luo-Xia-Hong SONG telescope primary mirror, and the 1.6 m multi-channel photometric survey telescope primary mirror at Yunnan University. However, due to risks in flipping larger mirrors and limitations in coating equipment and processes, IBAD has rarely been applied to mirrors over 2 m for wide-spectrum high-reflectivity coatings.

This paper presents the successful implementation of IBAD technology for a 2.5 m mirror after achieving safe flipping and hoisting. Using the 3.2 m vacuum coating facility at Nanjing Institute of Astronomical Optics & Technology, we investigated precise control of thin film optical constants and thickness uniformity across the 2.5 m aperture, obtaining wide-spectrum high-reflectivity reflective coatings and successfully completing their deposition on the 2.5 m primary mirror.

2. Optical Constant Consistency in 2.5 m Mirror Coatings

Wide-spectrum high-reflectivity coatings for astronomical applications typically consist of metal films plus dielectric films. The metal film provides fundamental reflectivity, while dielectric films serve as protective layers that reduce metal oxidation and enhance reflectivity across the working band. Face-down metal film deposition is mature and offers large growth tolerance. Therefore, the key challenge for large-aperture mirrors is precisely controlling dielectric film growth to achieve highly consistent optical constants.

The optical effect of dielectric films is described by the characteristic matrix:

$$\begin{bmatrix} \cos\delta_1 & i\eta_1 \sin\delta_1 \\ \sin\delta_1 & \cos\delta_1 \end{bmatrix}$$

where $\delta_1 = \frac{2\pi}{\lambda} d_1 \cos\theta_1$, with λ being the wavelength, θ_1 the refraction angle, and d_1 the film thickness. For the parallel (p) component, $\eta_1 = n_1/\cos\theta_1$, and for the perpendicular (s) component, $\eta_1 = n_1\cos\theta_1$, where n_1 is the film’ s effective refractive index. For real films with absorption, the refractive index extends to a complex form $n_1 - ik_1$, where k_1 is the extinction coefficient. The refractive index n_1 relates to material properties and packing density, reflecting hardness, stress, uniformity, and chemical stability. The product of refractive index and thickness constitutes the optical thickness, which determines optical properties, while the extinction coefficient represents light loss.

A simulated substrate was fabricated according to the 2.5 m primary mirror’ s surface figure. Made of stainless steel and lightweighted, it matches the actual mirror’ s dimensions, weight, and curvature [Figure 1: see original paper]. To verify coating properties, test pieces were placed at different positions on the simulated substrate. Since the substrate rotates during coating, test pieces were arranged radially from the central hole edge to the mirror edge, with eight test pieces uniformly distributed.

Based on the mirror shape, 3.2 m vacuum coating equipment geometry, and the ion source’ s linear energy distribution range, we independently set different ion source energy levels and beam current densities for Ta_2O_5 and SiO_2 materials. Using a Jeol electron gun, thick films of Ta_2O_5 and SiO_2 were deposited, and envelope algorithms were applied to calculate and fit the actual optical constants. [Figure 2: see original paper] and [Figure 3: see original paper] show the optical constant curves for Ta_2O_5 and SiO_2 films, respectively, at eight different positions (P1-P8) on the simulated substrate.

The results demonstrate that the deposited films have refractive indices close to ideal material values with low extinction coefficients. By partitioning and independently controlling dual ion source parameters according to the ion source’ s linear energy distribution, we obtained dielectric films with high packing density and excellent optical performance across the large aperture. The optical constants showed good consistency among the eight test pieces distributed radially on the simulated substrate.

3. Film Thickness Uniformity Study for 2.5 m Mirrors

During large mirror coating, dielectric film thickness uniformity critically affects reflectivity. Poor uniformity can shift reflectance peak wavelengths and even cause visible color differences across the mirror surface, impacting observations.

Film thickness uniformity depends strongly on evaporation source characteristics and the geometric configuration of equipment and mirror. For the 2.5 m mirror IBAD process, we used a face-down orientation with the substrate rotating about its center. To achieve better stability and uniformity, we employed a planar evaporation source with directional vapor emission limited to a hemisphere. The film thickness at any point on the mirror surface is given by:

$$t = \frac{m \cos^j \phi \cos \theta}{\mu r^2}$$

where m is the total evaporated material mass, ϕ is the emission angle (between the source normal and line connecting source to coating surface element), θ is the deposition angle (between surface normal and line connecting source to element), μ is material density, r is the distance from source to coating surface, and j is a source-characteristic coefficient. Prior experiments indicated $j = 2.7$ for Ta_2O_5 and $j = 4.3$ for SiO_2 under our process conditions.

For coating the 2.5 m primary mirror in the 3.2 m facility, we established a coordinate system with the mirror vertex as origin, Z-axis vertical upward (opposite to the vertex normal), and XY plane as the tangent plane at the vertex. The Y-axis points from the projection of the evaporation source onto the XY plane toward the origin. The spatial geometric configuration is shown in [Figure 4: see original paper], where h is the vertical distance from deposition point to source, H is the vertical distance from mirror center to source, $\vec{V}_1$ is the vector from surface point S to the source, $\vec{V}_2$ is the normal vector at S, α is the angle between the line connecting S to the vertex and the Y-axis. The 2.5 m primary mirror is aspheric, with its sag (difference between H and h) given by:

$$H - h = \frac{c\rho^2}{1 + \sqrt{1 - (1+k)c^2\rho^2}}$$

where c is mirror curvature, k is the conic constant, and R is the radius of curvature.

The geometric relationships in the 3.2 m coating equipment are:

$$r^2 = h^2 + (L + \rho)^2 - 4L\rho \sin^2 \frac{\alpha}{2}$$

where r is the magnitude of $\vec{V}_1$, L is the distance from source to chamber base center, and ρ is the radial distance of S' s projection from the vertex. The emission angle ϕ is calculated from h and r:

$$\cos\phi = \frac{h}{r}$$

The deposition angle θ is the dot product of $\vec{V}_1$ and $\vec{V}_2$ divided by their magnitudes:

$$\cos\theta = \frac{\vec{V}_1 \cdot \vec{V}_2}{|\vec{V}_1||\vec{V}_2|}$$

Substituting these equations and integrating yields the film thickness distribution for different H values. Based on the 3.2 m facility dimensions, we evaluated $H = 1100, 1200, 1300, 1400$, and 1500 mm. [Figure 5: see original paper] shows Ta_2O_5 thickness distributions for the 2.5 m mirror at different heights (Max indicates maximum non-uniformity), while [Figure 6: see original paper] shows SiO_2 distributions.

The simulations reveal relatively small thickness non-uniformity when the mirror center height is 1300–1500 mm. Considering the thickness distribution from central hole to mirror edge and the evaporation characteristics, we selected $H = 1350$ mm as the optimal deposition height. Using the thickness distribution at $H = 1350$ mm, we designed a correction plate using the arc-length correction method and refined it experimentally. Spectrophotometer measurements of single-layer films at positions 1–8 on the simulated substrate show consistent transmittance curves across 300–1700 nm [Figure 7: see original paper] and [Figure 8: see original paper].

Using envelope algorithms, we determined the actual thicknesses of Ta_2O_5 and SiO_2 films at different positions, as shown in . The thickness non-uniformity is 1.11% for Ta_2O_5 and 1.18% for SiO_2, both better than 1.2%.

4. Wide-Spectrum High-Reflectivity Coating for 2.5 m Aspheric Mirror

The 2.5 m aspheric mirror spectral requirements specify average reflectivity >90% across 350–1700 nm, with >95% reflectivity at 532 nm, 1064 nm, and 1550 nm. We designed a 12-layer enhanced aluminum coating with alternating Ta_2O_5 and SiO_2 dielectric layers on top of the aluminum film. The dielectric layers enhance the aluminum' s reflectance spectrum while protecting it, effectively improving durability and environmental resistance.

Eight test pieces placed at different positions on the simulated substrate were coated with the enhanced aluminum system. The reflectance curves [Figure

9: see original paper] show an average reflectivity of 91.3% across the required band, meeting specifications, with >95% reflectivity at 532 nm, 1064 nm, and 1550 nm.

Following GB/T 26332.4-2015 standards, we tested coating adhesion by applying wide adhesive tape to the surface and rapidly pulling it perpendicular to the film. After multiple repetitions, no delamination occurred, confirming excellent film adhesion. The wide-spectrum high-reflectivity coating was successfully completed on the 2.5 m aspheric mirror [Figure 10: see original paper].

Measurements of witness pieces on the workholder [Figure 11: see original paper] confirm that coating requirements were met.

5. Conclusion

Ion beam-assisted deposition technology can produce excellent wide-spectrum high-reflectivity coatings across a 2.5 m aperture. By matching ion source linear distribution ranges and analyzing the relative positions of electron guns, ion sources, and substrates, we independently controlled dual ion source parameters to achieve high-performance films with consistent optical constants across the 2.5 m aspheric surface. Through calculations of the spatial geometry between mirror and evaporation source and the mirror surface figure in the 3.2 m vacuum coating facility, we determined the optimal mirror height for best uniformity. Correction plate shape and parameters were established based on the thickness distribution, improving thickness uniformity to better than 1.2% for both Ta_2O_5 and SiO_2 films on the 2.5 m aspheric mirror. This method successfully completed the wide-spectrum high-reflectivity coating development and can be applied to subsequent telescope projects including the 1.9 m telescope at Beijing Normal University and the 2.5 m telescope at Nanjing University.

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