Geometry optimization in planetary rotation stage for thickness uniformity of films on spherical substrates

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We report the simulation results on the thickness uniformity of optical coatings deposited on spherical substrates by optimizing the geometric configuration parameters, such as tilting angle of the substrate holder and position of the evaporation source in a 1 000-mm-diameter planetary rotation stage (PRS). We reveal that good film uniformity on convex spherical surfaces or flat substrates, as well as concave surfaces with weak to moderate curvatures can be obtained through appropriate tilting of the substrate holder. For 300-mm-diameter substrates with clear aperture to radius of curvature (CA/RoC) between –0.3 and 0.7, the achievable film uniformity is above 99%. The source position is optimized to achieve good film uniformity.

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Accurately designed optical coatings are always deposited onto optical element surfaces for spectral performance improvement. For preparation of optical coatings on large-diameter optical elements, physical vapor deposition with sputtering or thermal evaporation through resistive boat or electron beam gun is generally employed[1−6]. In the coating process, controlling the film thickness uniformity is a crucial but challenging task. Without properly controlling the film thickness uniformity, the film non-uniformity induced spectral shifts and/or wavefront distortions of reflected and/or transmitted optical beams over the element surfaces might lead to dramatic degradation in performance of optical systems[7−10]. Moreover, many precise imaging systems generally contain spherical lenses, with some having large ratio of clear aperture to radius of curvature (CA/RoC). Conventionally, the control of film thickness uniformity is realized by coating with simple or planetary rotation systems. With the growing demand for higher film thickness uniformity in precise imagining applications, new thickness controlling methods were proposed and demonstrated, which could be classified into two kinds. The first kind is based on the carefully designed shadowing masks in combination with rotating substrates. Although masking is a simple and efficient method for film thickness uniformity improvement, it can also introduce undesirable problems. The use of shadowing masks could result in irregular and unpredictable spatial variations in film thickness, particularly in deep ultraviolet (DUV) coatings, which further cause impediments to precision optics production[10,11]. The second kind is based on geometry optimization of the coating plants, without shadowing masks. For instance, Gross *et al.*[1] realized optimization of coating uniformity in an ion beam sputtering system using a modified planetary rotation stage (PRS). Meanwhile, Wang *et al.*[12] demonstrated a method for uniform coating on a flat surface with diameter close to the coating chamber. In spite of the possible problems related to the use of shadowing masks, currently the masking technique is still the most widely employed method to control the thickness uniformity of optical coatings deposited on spherical substrates with large diameters.

In this letter, we propose a method to control the film thickness uniformity on spherical substrates that can be easily realized experimentally. We demonstrate that on spherical substrates (as well as flat substrates) film thickness uniformity can be improved by optimizing the configurations such as substrate holder tilting angle in PRS coating plant based on semi-empirical theoretical investigations. The method helps to achieve better film thickness uniformity for similar deposition parameters. It works especially well if CA/RoC values of the substrates are within −0.3 to 0.7 for substrates with CA=300 mm in a 1 000-mm-diameter PRS, where minus sign denotes the concave surface. We also optimize source position for film thickness uniformity improvement.

According to Holland and Steckelmacher's theory[13], based on the molecules emission pattern, a small-area evaporation source can be treated as a point source that emits molecules isotropically or a surface source that emits molecules toward upper half space with the distribution modulated by $\cos^n\varphi$, where φ is the angle between normal to the source surface and the molecular emission direction[7,14]. The emitted molecules travel in high vacuum until land on optical elements surface. The molecular deposition rate associates with not only the molecular emission pattern $\cos^n\varphi$, but also the distance r from the source to the deposition position and the angle θ between the molecular emission direction and normal to surface at the deposition position. A simple but well-worked expression for the deposition rate is

$$D = C\frac{\cos\theta\cos^n\varphi}{r^2}. \quad (1)$$

For coating large-diameter substrates in PRS, the substrates are often positioned at the center of the substrate holder. During the substrate revolution, the coordinates of points on the substrate surface are described as function of time and the parameters associated with the deposition rate are calculated for every point at time t[6].

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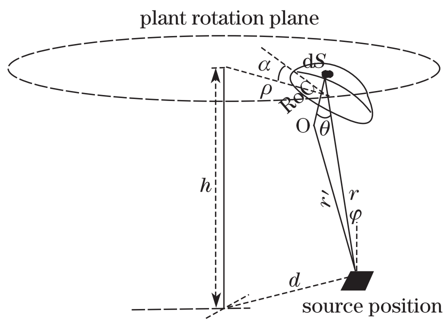

Fig. 1. Evaporation geometry on a tilted concave spherical substrate in planetary rotation system.

For example, for coating of a spherical surface in a plant with the substrate holder revolting parallel to the source surface, the point coordinates relative to the revolution center at time t are determined as

$$\begin{aligned} x(t) &= \rho\cos(\varpi_1 t) + \delta\cos(\varpi_2 t + \psi), \\ y(t) &= \rho\sin(\varpi_1 t) + \delta\sin(\varpi_2 t + \psi), \\ z(t) &= z_0, \end{aligned} \quad (2)$$

where ρ is the radius of the revolution orbital, and ϖ_1 and ϖ_2 are the angular velocities for planet revolution and rotation. $(\delta\cos(\varpi_2 t+\psi), \delta\sin(\varpi_2 t+\psi), z_0)$ are the coordinates of the surface point relative to the center of the substrate holder with initial position $(\delta\cos\psi, \delta\sin\psi, z_0)$. As z_0 is determined by δ for specified substrate geometry, the initial position is determined merely by δ and ψ.

For deposition on tilted substrate as denoted in Fig. 1, the coordinates of the point $(x1, y1, z1)$ relative to the center of substrate holder are obtained by rotating the coordinates $(\delta\cos\psi, \delta\sin\psi, z_0)$ with angle α about the vector $(-\sin(\varpi_2 t), \cos(\varpi_2 t), 0)$. The resulting coordinates relative to the center of substrate holder become

$$\begin{pmatrix} x_1 \\ y_1 \\ z_1 \end{pmatrix} = \begin{pmatrix} \cos\alpha + (1-\cos\alpha)\sin^2\varpi_2 t & -(1-\cos\alpha)\cos\varpi_2 t\sin\varpi_2 t & \sin\alpha\cos\varpi_2 t \\ -(1-\cos\alpha)\cos\varpi_2 t\sin\varpi_2 t & \cos\alpha + (1-\cos\alpha)\cos^2\varpi_2 t & \sin\alpha\sin\varpi_2 t \\ -\sin\alpha\cos\varpi_2 t & -\sin\alpha\sin\varpi_2 t & \cos\alpha \end{pmatrix} \begin{pmatrix} \delta\cos(\varpi_2 t+\psi) \\ \delta\sin(\varpi_2 t+\psi) \\ z_0 \end{pmatrix}. \quad (3)$$

The coordinates of the deposition point relative to the revolution center for tilting substrate are

$$\begin{aligned} x(t) &= \rho\cos(\varpi_1 t) + x_1, \\ y(t) &= \rho\sin(\varpi_1 t) + y_1, \\ z(t) &= z_1. \end{aligned} \quad (4)$$

The coordinates of the sphere's center after tilting are obtained similarly. For a specified coating plant, the distance between the evaporation source and the revolution center of the substrate is measured and the deposition parameters for substrates are calculated. For examples, for coating on a concave substrate with the center denoted by O, the radius of curvature by RoC, as denoted in Fig. 1, the deposition parameters are determined as

$$\begin{aligned} \theta &= \arccos\Big(\frac{r^2 + \mathrm{RoC}^2 - r'^2}{2r\times\mathrm{RoC}}\Big), \\ \varphi &= \arctan(\rho'/h'), \\ r &= \sqrt{\rho'^2 + h'^2}, \end{aligned} \quad (5)$$

where r' is the distance between the evaporation source and the center of the spherical surface, and ρ' and h' are the horizontal and vertical distances from the deposition point to the source, respectively. As the deposition rate is a function of time, the depositing film thickness is obtained by numerical integration of the deposition rate over time. For convex and flat substrates, the film thickness distributions are calculated similarly.

The film thickness distribution is simulated by modeling the coating process with thermal evaporation from a small-area evaporation source in a typical 1 000-mm-diameter PRS. The clear apertures of the studied substrates are assumed to be 300 mm, which is close to the diameter of the substrate holder. The radius of revolution orbital is 300 mm, and the vertical distance between the source plane and substrate holder revolution plane is 700 mm. We further assume that the radius of the revolution orbital and the vertical distance between the source plane and the substrate holder revolution plane keep invariable when the substrates tilt. The relative angular velocity of the substrate revolution relative to rotation is 17/131. The adopted emission pattern of the source is $\cos^2\varphi$.

We calculate the dependence of the film thickness distribution on substrate tilting angle. As the microstructural properties such as the surface roughness of deposited film depend strongly on the deposition parameter θ, rough surfaces will be formed with a large angle θ or θ varies in a wide range, which is not suited for optical film preparation[15,16]. Accordingly the tilting angle is limited in the range from –20° to 50°. We also assume that the evaporation source locates exactly below the revolution orbital, that is, 300 mm away from the center of the plant. The film uniformities of three 300-mm-diameter substrates are calcu lated: a flat substrate, a convex spherical substrates with RoC=250 mm and a concave spherical substrates with

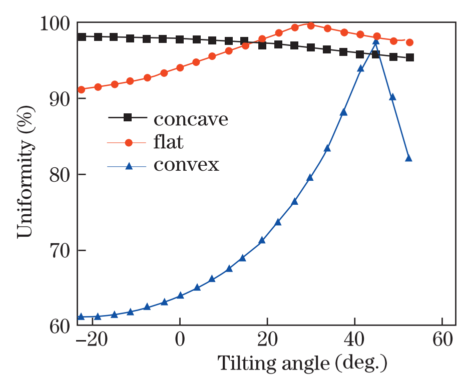

Fig. 2. (Color online) Dependence of film thickness uniformity on tilting angle for flat (circles), concave (squares), and convex (triangles) spherical substrates, respectively.

RoC=–380 mm. Figure 2 shows the resulting film uniformities as functions of the tilting angle for the three substrates. The results indicate that the film uniformity on the flat substrate and the convex spherical substrate changes drastically with the substrate tilting angle. For example, the film uniformity for the flat substrate has been increased from 93.5% to 99.5% by tilting the substrate to 30.0°. Meanwhile, film uniformity for the CA=300 mm, RoC=250 mm convex substrate is enhanced to 97.5% by tilting the substrate to 45°. On the other hand, the film uniformity for the concave substrate with RoC=–380 mm shows only weak dependence on the tilting angle.

For spherical substrates with different CA/RoCs, the best achievable uniformity and the corresponding substrate tilting angle are presented in Fig. 3. It is revealed that with the increase of CA/RoC from 0 to 1.4, the corresponding tilting angle increases while the best achievable film uniformity decreases gradually. For CA/RoC between 0 and 0.7, the achievable uniformity is better than 99.0% , and the corresponding tilting angle is between 30° and 37.5°. When CA/RoC increases to 1.0, the best achievable uniformity is about 98% . Meanwhile, for concave substrates with CA/RoC between 0 and −0.3, the uniformity above 99% is also achievable by tilting the substrate holder. On the other hand, for concave substrate with CA/RoC from −0.4 to −1 the uniformity is optimized when the substrates are −20° tilted. In this case, setting the substrate parallel to the source surface is preferred for a better film surface roughness holography. For coating on a CA=300 mm concave substrate with CA/RoC$<$ −0.7, film uniformity cannot be improved to better than 98% by tilting the substrate only. For such substrates

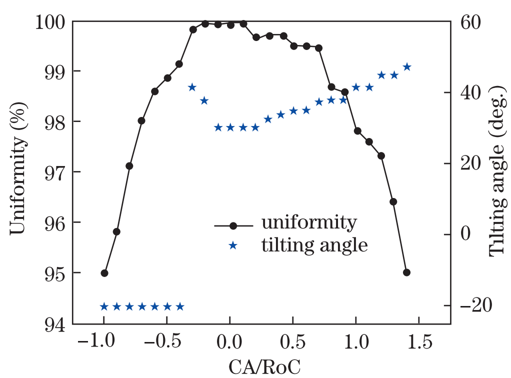

Fig. 3. (Color online) Best achievable film thickness uniformity (squares) for substrates with different CA/RoCs and the corresponding substrate tilting angles (stars).

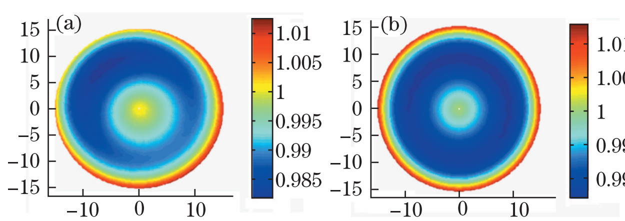

Fig. 4. (Color online) Film thickness uniformity for RoC=250 mm convex substrates after (a) 20 and (b) 50 revolutions.

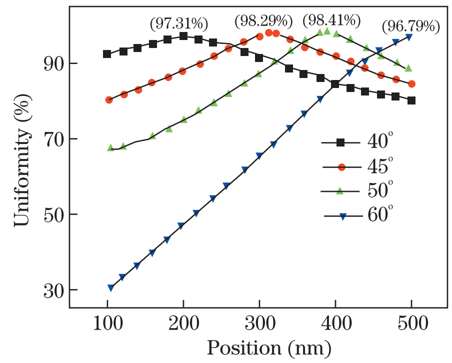

Fig. 5. (Color online) Dependence of the film uniformity on source position for RoC=250 mm convex substrate with differently tilting angles.

masking technique is essential for uniformity correction.

Figure 4 shows the film thickness distribution on a CA=300 mm and RoC=250 mm convex spherical substrate by tilting the substrate to 45°. Figure 4(a) demonstrates the film thickness distribution after about 20 revolutions. Different from the film thickness distribution after 50 revolutions as shown in Fig. 4 (b), film thickness distribution is rotationally unsymmetrical, although the uniformity is almost the same. For weakly curved and flat substrates, on the other hand, uniformity can be achieved with much less revolutions. Taking the 30.0° tilted 300-mm flat substrate as an example, after one revolution the film thickness uniformity is already 98% . The revolution is much less than using correcting mask. This means that for similar deposition parameter such as deposition rate and film thickness uniformity, film thickness uniformity would be much better after the similar deposition procedure. The unsymmetrical film thickness distribution is introduced by slow rotation speed of the substrate holder compared to the revolution speed, which can be improved by increasing the angular speed of the substrate holder rotation. For example, when the angular velocity of the substrate revolution to rotation changes to 10/137, film thickness uniformity similar to Fig. 4(a) can be realized in about 5 revolutions for the same substrate.

We also optimize the film thickness uniformity by changing the source position, which is characterized by the offset from the center of the coating plant, as denoted by d in Fig. 1. It is found that film thickness uniformity on tilted substrates are much better than that on substrate parallel to the substrate surface. Figure 5 shows the source position dependent film thickness distribution on a RoC=250 mm convex substrate with substrate holder tilted by different angels. It is seen that the source position for achieving the best uniformity is dependent on tilting angles. With the increasing of tilting angle, the source position that leads to best uniformity moves toward the rim of the substrates. Meanwhile, the best achievable uniformity depends on tilting angles. For the studied substrates, the best uniformity is above 98% when the tilting angle is between 45° and 50°. From the consideration of use efficiency of coating material and film surface morphologies, the substrate tilting angle of 45° is better for uniform coating, and the corresponding optimal source position is about 300 mm from the center of the plant, which is below the revolution orbital. For other spherical substrates, similar results are concluded from our simulation.

In conclusion film thickness uniformity on 300-mm-diameter spherical substrates can be improved by optimization of the substrate holder tilting angle and evaporation source position. The substrate tilting angle corresponded to the best achievable uniformity increases gradually with the absolute value of CA/RoC for convex and concave substrates. For substrates with CA/RoC between –0.3 and 0.7, film uniformity above 99% can be realized by tilting substrates. For coating spherical substrates, the optimal source position locates below the substrate revolution orbital. The simulation results can help to promote a practical approach for controlling the film thickness uniformity on spherical substrates.

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