Optimization of the spectral performance of an antireflection coating on a micro-spherical substrate

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To improve the optical performance of an antireflection (AR) coating on a micro-spherical substrate, the ray angle of the incidence distribution and the thickness profile are taken into consideration during the optical coating design. For a convex spherical substrate with a radius of curvature of 10 mm and a clear aperture of 10 mm, three strategies are used for the optimization of the spectral performance of a broadband AR coating in the spectral region from 480 to 720 nm. By comparing the calculated residual reflectance and spectral uniformity, the developed method demonstrates its superiority in spectral performance optimization of an AR coating on a micro-spherical substrate.

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An antireflection (AR) coating is a common thin-film optic normally used to increase the intensity of light throughout and improve the contrast of the image in an optical system. Thanks to its performance, AR coatings make up more than half of the total thin-film market and play an important role in a lot of optical equipment. The preparation of high-quality AR coatings requires careful maximization of the transmittance and improvement of the environmental resistance at a comparably low cost. In the past, plenty of investigations have been performed to optimize the optical coating design and deposition process[1–5]. Nevertheless, for most precision optical system applications, optical micro-spherical lenses are increasingly used due to their many and novel industrial purposes[4,6,7]. These micro-spherical elements must be AR coated in order to enhance their optical performance, but achieving perfect throughput and transmission uniformity across the micro-components is very challenging owing to the shape and small size. Normally, system performance requirements extend to the AR coatings fabricated on these elements.

The spectral performance of an AR coating is determined in general by the coating design. To optimize the AR coating design, several issues must be properly addressed, such as the ray angle of incidence (AOI), individual layer thicknesses, and the refractive indexes of the layer materials. First, the steepness of the spherical surface can result in the AOI having a wide distribution over the lens. Second, strongly curved element coating materials present various thicknesses and refractive index distributions. As a result, the optical coating will yield varying spectral performances at different locations on the lens. Up to now, the preparation of a uniform thin film on a spherical substrate involved using a coating machine with a planetary rotation system, which provides a great degree of randomization and therefore reduces the effect of deposition fluctuation. For a spherical substrate with a large dimension, the spectral uniformity of thin film can be further improved with the help of a shadowing mask[8,9]. Unfortunately, the method is not suitable for a micro-spherical substrate. Thus, major efforts have been focused on optical coating design for micro-components. Most recently, Isfort *et al.*[4] have reported some results on the optimization of the optical coating design of a micro-spherical lens, taking the thickness and refractive index distributions into consideration. It is also demonstrated that in most cases, the refractive index of the layers can be approximately treated as a constant across the micro-spherical lens. By contrast, the influences of the AOI distribution and thickness profile on the spectral performance of optical coating are very serious. However, in the literature, there is no document on the improvement of the optical coating performance by taking into account the ray AOI distribution and thickness profile over the micro-spherical substrate.

In the present work, to maximize the throughput and transmission uniformity across the micro-spherical substrate, an AR coating design was comprehensively optimized with the thickness distribution and the AOI profile. For comparison, another two AR coating designs were presented for use at a normal incidence angle and wide angular range without taking the thickness profile into account. The theoretical analysis suggested that the developed design method worked very well for the spectral performance optimization of the AR coating on a micro-spherical substrate.

Let us consider a convex spherical substrate coated with a broadband AR coating in the spectral region from 480 to 720 nm. The geometrical parameters of the micro-spherical lens are the clear aperture (CA) of 10 mm and the radius of curvature (RoC) of 10 mm. Assume a beam of parallel light is converged through the convex spherical surface, as illustrated in Fig. 1(a). The steepness of the curved substrate can lead to the ray AOI having a wide range across the coated surface. Currently, the light AOIs for the spherical substrate are linearly varied from 0° to 30° along the radial direction of the CA, as shown in Fig. 1(b).

According to Knudsen's law[10], the deposition of a thin film can be essentially treated as an illumination problem. The theoretical thickness distribution of the thin film deposited on the spherical substrate can be calculated via a model reported in Ref. [8]. For a given coating plant configuration, the thickness profile of a thin film can be influenced by both the angle of inclination of the planetary carrier and the emission characteristic parameter of the source. In the theoretical analysis, the geometric parameters of the vacuum coating machine were the same as those presented in Ref. [7]. The dependence of the thickness uniformity on the angle of inclination and the emission characteristic parameter are presented in Fig. 1(c). As shown in Fig. 1(c), during the variations of the angle of inclination from 0° to 40° and the emission characteristic parameter from 0 to 4, the thickness uniformity of the thin film on the spherical substrate ranges between 86.08% and 86.26%. It is suggested that the thickness distribution cannot be improved by the optimization of the angle of inclination of the planetary carrier. Although shadowing masks can be applied to correct the thickness distribution, as documented in Refs. [8,9], taking the utilization efficiency of the materials into account, the dimension of the most effective mask should be smaller than the diameter of the CA. Clearly, the shadowing mask is too small to be employed for the thickness correction of the micro-spherical substrate. To analyze the spectral performance of the AR coating deposited on the whole micro-spherical substrate, the angle of inclination and the emission characteristic parameter are set to 0° and 2, respectively. The calculated thickness distribution of the thin film along the radial direction of the CA is exhibited in Fig. 1(b) as well.

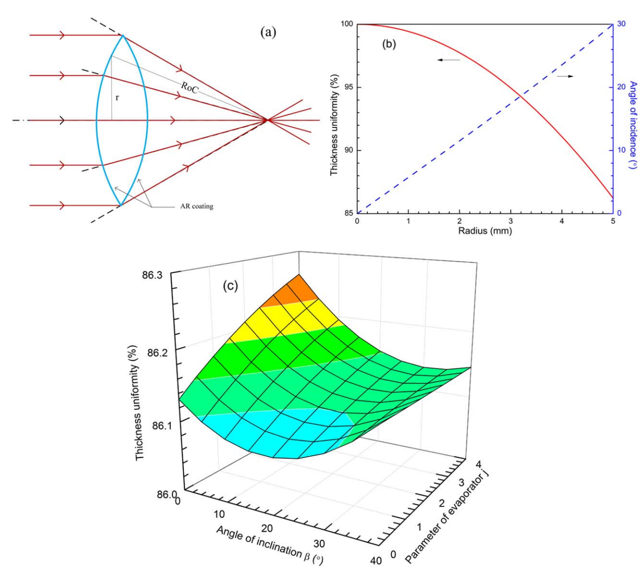

Fig. 1. (a) Geometric sketch map for ray trace of a spherical substrate, (b) the calculated thickness profile and light angle of the incidence distribution, and (c) the calculated dependence of the thickness uniformity on the angle of inclination and the emission characteristic parameter.

To improve the spectral performance over the spherical substrate, it is necessary to take the AOI distribution and thickness profile into account during the AR coating design. To address the importance, three designs are selected to minimize the average reflectance from 480 to 720 nm, that is, D1 is optimized for use at the normal incidence angle, while D2 is selected for application over a large AOI range from 0° to 30°. Both D1 and D2 are achieved by Optilayer software without considering the thickness distribution on the micro-spherical substrate[11]. D3 is optimized for the comprehensive optical performance of the thin film over the micro-spherical substrate by a MATLAB script implemented using a simulated annealing algorithm. The optical design theory is already well documented in Refs. [12,13] and is not presented in the Letter. For three designs in the interested spectral range, the ambient medium is set to be air with $n_a = 1$. BK7 is used as the substrate, and Ta_2O_5 and SiO_2 are chose as the high- and low-index materials. The refractive indexes of the substrate and the low- and high-index materials are shown in Fig. 2. The refractive indexes of the layers are treated as constant throughout the micro-spherical substrate. Because the ratio CA/2Roc is smaller than 0.7, it is reasonable according to Ref. [4]. Moreover, both the coating layers and the substrate are taken as non-absorbing materials. Next, based on three different optimization strategies, the corresponding best design results are achieved and demonstrated in Table 1. In the design configuration, the first layer is close to the substrate, and the last layer is near the air. The correspondingly calculated spectral performances of the AR coatings on the micro-spherical substrate are presented in Fig. 3.

Figures 3(a)–3(c) show the calculated residual reflectance of the D1–D3 designs for 6 locations on the spherical surface, where r is the horizontal distance from the coated location to the central axis of the micro-spherical

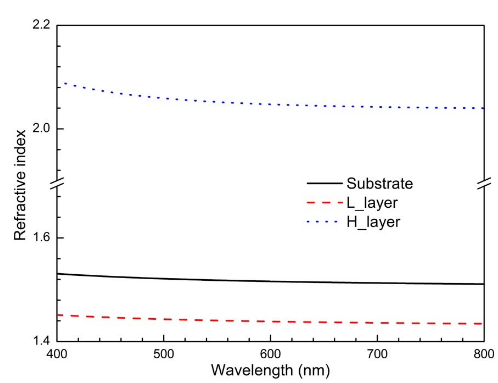

Fig. 2. Refractive indexes of the substrate and the low- and high-index materials for the AR coating design.

Table 1. Parameters of Three AR Coating Designs for 480–720 nm Spectral Region

	Multilayer Structure
D1	15 nmH 42.81 nmL 153.54 nmH 233.16 nmL 18.2 nmH 165.17 nmL 25.76 nmH 23.22 nmL 83.04 nmH 120.96 nmL 18.56 nmH 38.42 nmL 79.68 nmH 118.14 nmL 16.83 nmH 45.02 nmL 79.24 nmH 98.06 nmL 15 nmH 61.67 nmL 75.17 nmH 101.44 nmL
D2	17.74 nmH 38.6 nmL 180.14 nmH 18.65 nmL 118.12 nmH 27.89 nmL 33.23 nmH 95.12 nmL 56.82 nmH 22.73 nmL 64.14 nmH 105.93 nmL 38 nmH 27.31 nmL 79.93 nmH 107.7 nmL 26.56 nmH 35.19 nmL 86.95 nmH 110.28 nmL 15.08 nmH 56.02 nmL 77.23 nmH 103.8 nmL
D3	44.3 nmL 22.26 nmH 44.85 nmL 190.65 nmH 21.63 nmL 204.79 nmH 36.22 nmL 69.86 nmH 26.57 nmL 74.48 nmH 74.39 nmL 31.94 nmH 53.83 nmL 112.12 nmH 46.14 nmL 22.8 nmH 105.87 nmL 163.84 nmH 84.03 nmL 33.13 nmH 39.05 nmL 89.5 nmH 109.59 nmL

substrate as exhibited in Fig. 1(a). As r increases, the reflectance curves shift towards short wavelengths. This result is due to the variations of the AOI and thickness. Obviously, the largest reflectance deviation between the vertex and the edge of the micro-spherical substrate is exhibited when the AR coating design is only optimized at a normal incidence, as shown in Fig. 3(a). The reflectance uniformities are improved if the design is treated with a wide range of incidence angles, as exhibited in Fig. 3(b). In the meantime, the best results are obtained if both the AOI distribution and the thickness profile are taken into consideration, as shown in Fig. 3(c). The calculated average reflections of the D1–D3 designs on the micro-spherical substrate are presented in Fig. 3(d). As shown in the pictures, the effective dimensions of the D1–D3 designs with average reflectances below 0.25% are approximately 2.4, 3.3, and 5 mm, respectively. The corresponding area ratios between the effective dimension and the CA are then determined to be 23%, 43.6%, and 100%. It is suggested that the developed method is particularly suitable for optical coating designs for micro-spherical substrates.

In conclusion, a method for optical coating design taking into account the thickness distributions of the layer materials and the AOI profile are proposed and applied to optimize the spectral performance of the anti-reflection coating formed on a micro-spherical substrate. The calculated spectral performance of the AR coating indicates that maximum output and transmission uniformity over the curved surface can be achieved. The proposed method would be of great importance to the preparation of multilayer stacks with highly uniform spectral performances on strongly curved spherical or quasi-spherical substrates, but also for those with large flat lenses.

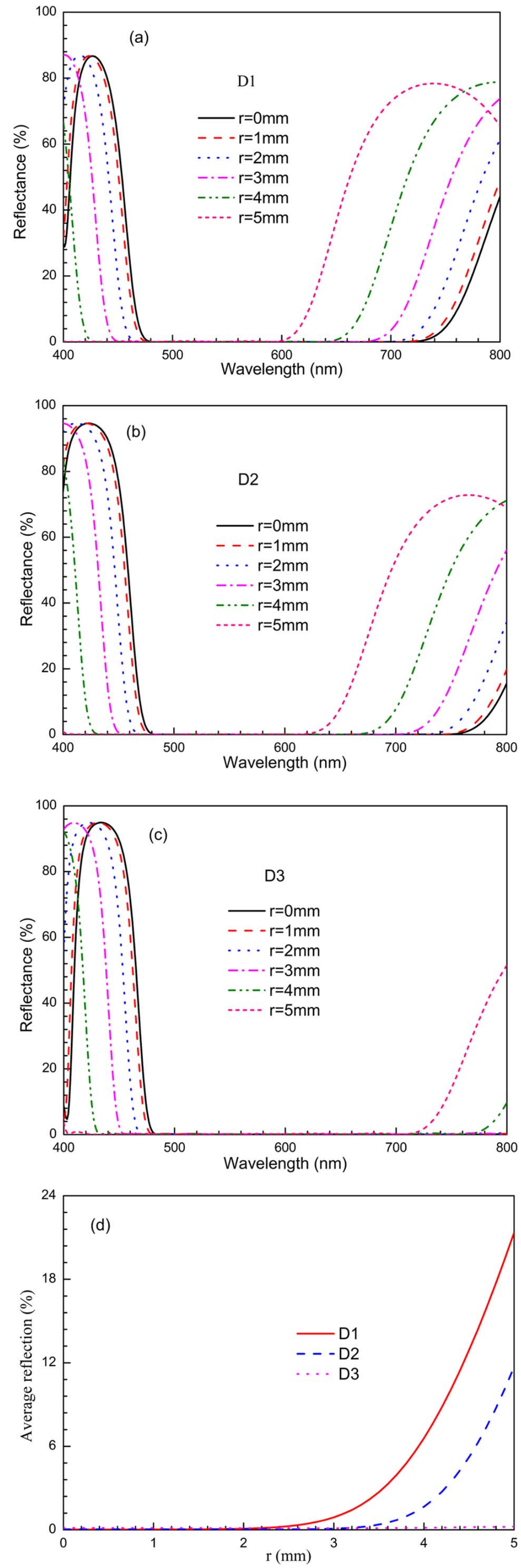

Fig. 3. Residual reflections and spectral uniformities of three AR coatings.

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