Design of anisotropic reflector with birefringent thin films

Jianguo Wang (王建国), Kui Yi (易 葵), Jianda Shao (邵建达), and Zhengxiu Fan (范正修)

Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800

Received July 2, 2004

A novel design for dielectric anisotropic mirrors with birefringent thin films for normal incidence is presented. This mirror consists of a stack of quarter-wave biaxial layers. The biaxial anisotropic layers can be fabricated by oblique deposition. The reflectance is different for two linear polarizations of light incidence on the mirrors. As a numerical example, the design is carried out on glass with TiO_2 and ZrO_2. These thin films could be applied to anisotropic reflective devices for lasers.

OCIS codes: 260.1180, 310.1620, 260.1440, 310.0310.

Mirrors reflecting normal incident light anisotropically have many applications in laser optics. The most radical method for producing polarizing mirrors involves the use of strip metal gratings with a sub-wavelength period; variation of this period and of the strip width make it possible to control the mirror characteristics[1]. The use of metal gratings is limited to the infrared range, since metals cannot ensure the necessary low losses and high reflectance at visible wavelengths. Conventionally antireflection coatings and phase compensator coatings etc.. have been designed with the combination of a quarter-wave layer H with a high reflective index $n_{\rm H}$ and a quarter-wave layer L with a low reflective index $n_{\rm L}$[2,3]. But it is difficult to use these isotropic layers to design anisotropic reflectors.

When thin films are deposited onto stationary substrates with the flux arriving at a non-normal angle under conditions of limited adatom diffusion, an inclined columnar microstructure is produced. By controlling the orientation of the substrate relative to the impinging vapor flux, the columnar microstructure can be tailored with the range of control dependent on the material and deposition conditions. A dielectric thin film deposited obliquely behaves like an orthorhombic crystal and exhibits biaxial optical properties[4]. The parameters of an anisotropic layer can be controlled to some extent by altering the angle of deposition and the thickness of the coating material[5]. It has been suggested that anisotropic dielectric coating can be designed as antireflection coatings, polarizers, retarders, etc.[6−9].

In this letter we investigate the optical properties of a dielectric thin-film reflector that is planar and is designed for use with laser light at normal incidence. The mirror is a stack of biaxial films so that there is no cross coupling of polarizations for light at normal incidence. We assume that the biaxial anisotropic thin films are homogeneous and nonmagnetic. One period of the stack and the polarization directions are shown in Fig. 1. P is the direction of vibration of light that is rejected through the polarizer and S is the vibration direction of light that is rejected partially. The values of the refractive indices n_{p1}, n_{s1}, n_{p2}, and n_{s2} are determined by the anisotropic shapes and packing of the thin-film columnar nanostructures, and the p and s subscripts correspond to parallel and perpendicular to the incidence planes, respectively.

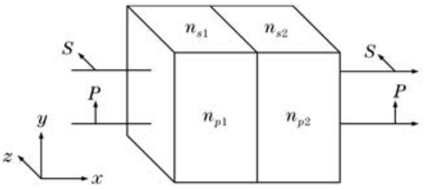

Fig. 1. Refractive indices of the layers that form one period of the anisotropic reflector. Incident light with p polarization encounters quarter-wave films with refractive indices n_{p1} and n_{p2} that satisfy a condition for zero reflectance; s-polarized light sees refractive indices n_{s1} and n_{s2} and is partially reflected.

In this case, incident light polarized in the p sense will not produce any s component of reflected and refracted light and *vice versa*, so that we can treat each of the polarizations separately, just as isotropic materials. Because the p and s polarizations propagate independently, standard results from the theory of isotropic multi-layers can be applied to the reflector. Light with the p polarization and the design wavelength λ_0 encounters a coexisting periodic high–low–high$\cdots$–low–high stack of quarter wave optical thickness layers with refractive indices n_{p1} and n_{p2}, and s polarization is to be rejected partially.

The reflectance of isotropic coating can be deduced from the Abelès matrix for $P_1P_2P_1$ combination, for p polarization light

$$R_p = \left[\frac{n_a - (n_{p1}/n_{p2})^{2N}(n_{p1}^2/n_g)}{n_a + (n_{p1}/n_{p2})^{2N}(n_{p1}^2/n_g)}\right]^2, \qquad (1)$$

for s polarization light

$$R_s = \left[\frac{n_a - (n_{s1}/n_{s2})^{2N}(n_{s1}^2/n_g)}{n_a + (n_{s1}/n_{s2})^{2N}(n_{s1}^2/n_g)}\right]^2, \qquad (2)$$

where N is the period in the stack, n_a and n_g are the indices of incident medium and substrate, respectively. The greater the number of layers, the higher the reflectance will be obtained.

The starting point for the design of the anisotropic reflector comes from recognition that the basic isotropic mirror design aH(LH)g can be extended to multiple periods, aH(LH)$^N g$. Light with external p polarization propagates without change of polarization and encounters quarter-wave layers of refractive indices n_{p1}, n_{p2}, n_{p1}, n_{p2}, $\cdots$, whereas s-polarized light encounters non-quarter-wave layers of refractive indices n_{s1}, n_{s2}, n_{s1}, n_{s2}, $\cdots$.

Obliquely deposited birefringent films are used to form the anisotropic reflector. Empirical equations[4] that provide values for the refractive indices n_p and n_s as functions of the deposition angle θ_ν can be used to determine suitable parameters for the anisotropic reflector. In terms of the constants A_0 and A_2 used by the empirical equation for the thin film, refractive index is[9],

$$n = A_0 + A_2\theta_\nu^2, \tag{3}$$

the solution for the deposition angle of the layer is

$$\theta_\nu = \{[n(n_g/n_a)^{1/2N} - A_0]/A_2\}^{1/2}. \tag{4}$$

In general, the theoretical performance of the coating improves (larger values of R_p and R_s) with increasing the integer N, but in practice a small number of periods is preferred to minimize losses due to absorption and scatter. Figure 2 shows the calculated spectral reflectance of a basic titanium oxide/zirconium oxide anisotropic reflector, and the associated values of the refractive indices are $n_a = 1$, $n_g = 1.5$, $N = 5$, $n_{s1} = 2.117$, $n_{s2} = 1.699$, $n_{p1} = 2.173$, $n_{p2} = 1.659$, and the design wavelength is 633 nm. The difference in reflectance, $R_p - R_s$, is 5.6% in this case.

Further calculations show that small changes in the basic anisotropic mirror design can lead to significant increase in R_s and R_p at the cost of a small decrease in reflective difference, and we have designed anisotropic mirror by using this principle. Figure 3 shows the calculated spectral reflectance of a titanium oxide/zirconium oxide design, in which we modified the refractive indices of the biaxial layers. The corresponding indices are $n_{s1} = 2.266$, $n_{s2} = 1.663$, $n_{p1} = 2.297$, and $n_{p2} = 1.621$. Figure 3 shows that R_p has increased from 91.8% to 97.8%, R_s from 86.2% to 96.8%, respectively, at the cost of decreasing the difference between R_p and R_s from 5.6% to 1.1%. A refractive-index profile for the modified anisotropic mirror is plotted in Fig. 4.

Further use of the empirical Eq. (4) with deposition angle $\theta_{\nu1}$ and gives n_{p1}, and so it is for $\theta_{\nu2}$. Calculations show that, $\theta_{v1} = 43°$, $\theta_{v2} = 55°$ can meet the requirement the reflective indices for the first design with titanium oxide/zirconium oxide, and $\theta_{v1} = 30°$, $\theta_{v2} = 60°$ for the modified design. Other dielectric materials can also be used to design the anisotropic reflector. The polarization contrast could be sufficient for some applications, for example, in multiple-beam interferometers and in laser cavities. Fabrication of the anisotropic reflector is being performed in our group, and will be reported later.

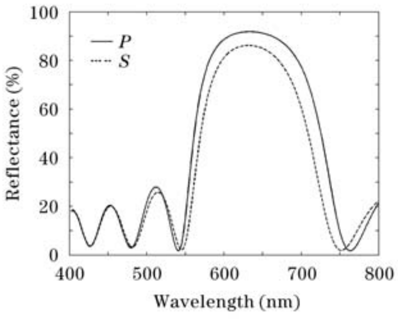

Fig. 2. Calculated spectral reflectance of a titanium oxide/zirconium oxide anisotropic reflector. The coating parameters are $n_a = 1$, $n_g = 1.5$, $N = 5$, $n_{s1} = 2.117$, $n_{s2} = 1.699$, $n_{p1} = 2.173$, and $n_{p2} = 1.659$.

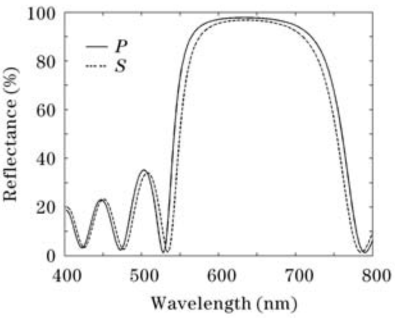

Fig. 3. Calculated spectral reflectance of a titanium oxide/zirconium oxide anisotropic reflector according to the modified design with $n_a = 1$, $n_g = 1.5$, $N = 5$, $n_{s1} = 2.266$, $n_{s2} = 1.663$, $n_{p1} = 2.297$, and $n_{p2} = 1.621$.

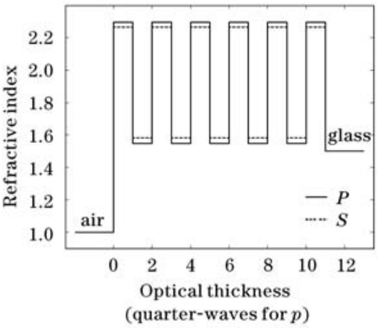

Fig. 4. Reflective-index profile of the titanium oxide/ zirconium oxide anisotropic reflector with the modified design.

In conclusion, we have studied the anisotropy of the reflectance of biaxial anisotropic multi-layers and the feasibility of constructing highly reflecting polarizing mirrors for normal light incidence. The phase thickness and the optical admittances of the layers are compensated using the birefringent properties of thin film. The novel design of anisotropic reflector is employing the birefringence of thin films, which have significantly application in laser optics in future.

J. Wang's e-mail address is wjg@siom.ac.cn.

References

1. Y. V. Troitskii and B. I. Troshin, Quantum Electron. **28,** 89 (1998).
2. L. R. Huang, L. H. Hui, Z. H. Hu, Y. Z. Huang, and D. X. Huang, Chin. J. Lasers (in Chinese) **30,** 633 (2003).
3. W. Lu, P. F. Gu, and X. Liu, Acta Opt. Sin. (in Chinese) **23,** 1123 (2003).
4. I. J. Hodgkinson and Q. H. Wu, *Birefringent Thin Films and Polarizing Elements* (World Scientific, Singapore, 1998).
5. I. J. Hodgkinson, Q. H. Wu, and J. Hazel, Appl. Opt. **37,** 2653 (1998).
6. I. J. Hodgkinson and Q. H. Wu, Appl. Phys. Lett. **74,** 1794 (1999).
7. A. Lakhtakia and M. McCall, Opt. Commun. **168,** 457 (1999).
8. I. J. Hodgkinson and Q. H. Wu, J. Opt. Soc. Am. A **18,** 975 (2001).
9. K. Kaminska and K. Robbie, Appl. Opt. **45,** 1570 (2004).