Double-wavelength polarization insensistive beam splitter used in optical storage technology

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Device to read/write data from optical storage units have polarization insensitive character at two separated wavelength. Based on a key four-layer structure and some matching layers, an initial thin film stack system is constructed. After optimized alternately by simplex and conjugate graduate algorithm, a double-wavelength polarization insensitive beam splitter with splitting ratio of $R:T$=50:50 at 650-nm wavelength and $T \geqslant 93\%$ at 780-nm wavelength is gained. The design result shows that the difference between reflectivity of P and S light around wavelength range of 630–670 and 760–800 nm with incident angle of 40°–50° is all very little. That indicates our design controls the polarization deviation well at two separate wavelengths with a reasonable range for both wavelength and incident angle.

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Optical thin film was widely used in optical and electric system as a fundamental component. But in general[1], plane waves at non-normal incidence on a dielectric optical thin film, having transverse electric and magnetic fields, respectively, will experience different reflectances of R_s and R_p. Such polarization effect can be used to design polarizers. However, control of polarization deviation plays an important role in some applications.

Many papers devoted to reduce the polarization deviation. For example, Baumeister[2] firstly studied optical interference coating technology and designed nonpolarizing beam splitters. Thelen[3] showed that a nonpolarizing beam splitter could be designed for the visible part of the spectrum if three or more quarter wave stack coating materials were used. Qi *et al.*[4] investigated nonpolarizing beam splitters based on the birefringent properties of a thin film. Subsequently, many other papers[5−13] were published on nonpolarizing all-dielectric beam splitters and Willey[14] interpreted nonpolarizing properties utilizing building-block patterns, which were theoretically and practically significant for the development of nonpolarizing beam splitters. We can find that most theoretical predictions and design procedures were valid for a limited wavelength and/or angular range. But ideally, the reflectance and transmittance of the s and p polarizations should be equal at required working wavelength region. Furthermore, the filter should also have a reasonable angular field and no losses.

All above design was most operated at a single wavelength or in a relatively narrow wavelength range. But in optical storage technology fields, the device used to read/write data from optical storage units need some beam splitter with little polarization deviation. One situation is polarization insensitive at two separate wavelengths, 650 and 780 nm, with different splitting ratios, respectively at incident angle of 45°. In this letter, we want to design this double-wavelength polarization insensitive beam splitter by constructing an initial thin film based on a four-layer structure and some matching layer, then it should be optimized alternately by simplex and conjugate graduate algorithm.

The polarization dependence of optical thin film used at non-normal incidence results from the Fresnel equations. The performance of thin films at oblique angles of incidence can be shown to be equivalent to the normal incidence performance of two design, one for each polarization. For p and s polarization, each index of refraction in the design, including the massive media indices, can be replaced by the effective index respectively. The expression was given by

$$\begin{cases} n_p = n/\cos\theta \\ n_s = n\cos\theta \end{cases}, \tag{1}$$

where n and θ are the index of refraction and the angle of incidence in corresponding layer or medium respectively. Polarization splitting is defined as

$$\Delta n = n_p/n_s = (\cos^2\theta)^{-1}, \tag{2}$$

which is easily shown that a single layer must have polarization splitting with n_p large than n_s when used at oblique angle of incidence.

But for a multilayer thin film system, each single layer related to a characterististic matrix respectively, and the characteristic matrix of assembly was simply the product of the individual matrices taken in the correct order.

$$\begin{cases} \begin{bmatrix} B \\ C \end{bmatrix} = \left\{ \prod_{j=1}^{k} \begin{bmatrix} \cos\delta_j & \dfrac{\mathrm{i}}{n_j}\sin\delta_j \\ \mathrm{i}n_j\sin\delta_j & \cos\delta_j \end{bmatrix} \right\} \begin{bmatrix} 1 \\ n_\mathrm{s} \end{bmatrix}, \\ \delta_j = \dfrac{2\pi}{\lambda} n_j d_j \cos\theta_j \end{cases} \tag{3}$$

where n_j, d_j, and θ_j are the index of refraction, physical thickness, and the angle of incidence in corresponding j layer respectively, and n_s denotes the refractive index of substrate or emergent medium. Then the optical admittance Y and reflectance R of assembly can be given as

$$\begin{cases} Y = \frac{C}{B} \\ R = \left(\frac{n_0 - Y}{n_0 + Y}\right)^2 \end{cases}, \quad (4)$$

where n_0 is the refractive index of incident medium. As the effective index of p and s light in each thin film layer was different, the polarization effect of multilayer thin film system was still strong at usual situation. But within special spectrum region with some incident angle range, control the polarization deviation with little error by choosing appropriate material combination was possible.

The principles of design to control polarization derivation have been elusive. The techniques which were currently available operate only over very restricted range of wavelength and angle of incidence.

Some already exist results has led to some insight a patterns of optical thin film layers that can contribute to control polarization effect. One pattern of four-layer structure medium-low-medium-high (MLMH) indices behaves somewhat like the typical two-layer pair of quarter-wave optical thickness (QWOT) layers at the design wavelength as used for normal incidence designs. This four-layer pattern can be used in much the same way as QWOT stacks are used at normal incidence, except that the designs are at high angles of incidence (such as 45°), which causes percent reflectance, percent transmittance all to be near the same in s and p polarization.

In this letter, we need design a beam splitter with litter polarization deviation at two wavelengths of 650 and 780 nm. And the required splitting ratio is $R : T = 50 : 50$ at 650-nm wavelength and $T \geqslant 93\%$ at 780-nm wavelength respectively. The incident medium is air, the substrate is glass K_9, and incident angle is 45°. Certainly, the beam splitter should have a reasonable widely range to wavelength and incident angle for error in actual application.

We chose MgF_2, Al_2O_3, and TiO_2 as low, medium, and high index material and their corresponding refractive indices were 1.37, 1.66, and 2.31 at 650-nm reference wavelength respectively. Their appreciable dispersion have also be handled properly in our whole design. These three thin film materials have little extinction index and can be used to composed a four-layer structure with little polarization deviation, which is the reason for our chosen. Then an initial thin film stack system of air|L $(MLMH)^{10}$H|glass was constructed by the use of these three dielectric material, where L, M, and H denoted quarter-wave optical thickness layers of MgF_2, Al_2O_3, and TiO_2, respectively, at the 650-nm reference wavelength as used for 45° incidence angle. In this thin film system, four-layer structure MLMH is the key pattern, which has the ability to move the current reflection to a higher level where the p and s polarization were closer to each other in reflection. The L and H layers adjacent to incident medium and substrate were matching layers respectively. The reflectance curve of this thin film stack at 45° as shown in Fig. 1.

To make the reflectance curve approach to the required objective better and have a reasonable range of wavelength and incident angle, the numerical method must be used to change thickness of each layer. The initial thin film stack system was optimized by simplex and conjugate graduate optimization algorithm alternately. The target was settled to control polarization deviation and required splitting ratio at the wavelength range of 630–670 and 760–800 nm with incident angle of 40–50°. The reflectance curve of this thin film stack system after optimization with incident angle of 45° is shown in Fig. 2

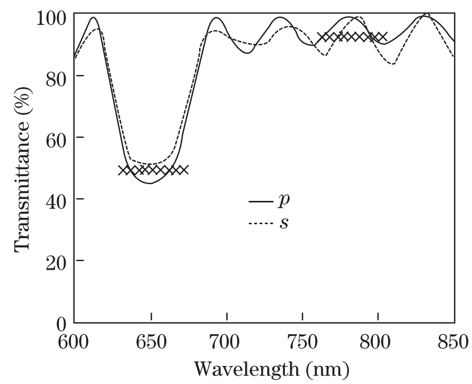

Fig. 1. Reflectance curve of initial thin film stack with incident angle of 45°.

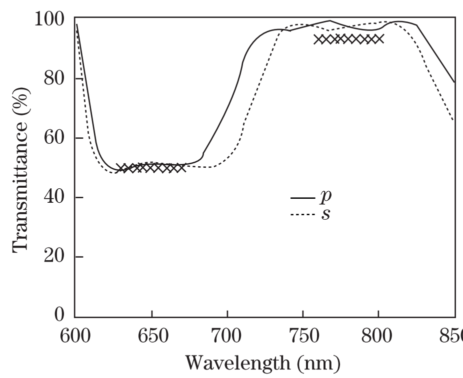

Fig. 2. Reflectance curve of thin film stack after optimization with incident angle of 45°.

Table 1. Physical Thickness of Each Layer Corresponding to Fig. 2

Incident Media	Air			
Matierial	MgF_2			
Thickness (nm)	98.37			
Matierial	$(Al_2O_3$	MgF_2	Al_2O_3	$TiO_2)^{10}$
Thickness (nm)	0.00	40.91	0.00	82.73
	74.28	159.25	98.83	79.07
	0.00	0.00	101.75	72.24
	138.96	114.26	109.27	71.59
	114.19	115.84	147.37	72.14
	74.76	0.00	0.00	93.62
	94.82	151.14	60.39	92.61
	126.60	54.16	64.53	56.98
	118.61	123.35	117.03	75.53
	134.26	95.83	98.54	0.00
Material	TiO_2			
Thickness (nm)	0.00			
Substrate	Glass (K_9)			

and it's corresponding physical thickness of each layer is shown in Table. 1.

To observe the change of reflectance curve at around two required wavelengths about incident angle factor, we show the reflectance curve in Figs. 3 and 4 with incident angles of 40°, 45°, and 50° corresponding to wavelength region of 630–670 and 760–800 nm respectively. From these two figures, we can find the differences between reflectivity of p and s light are all very little and can be neglected in actual application.

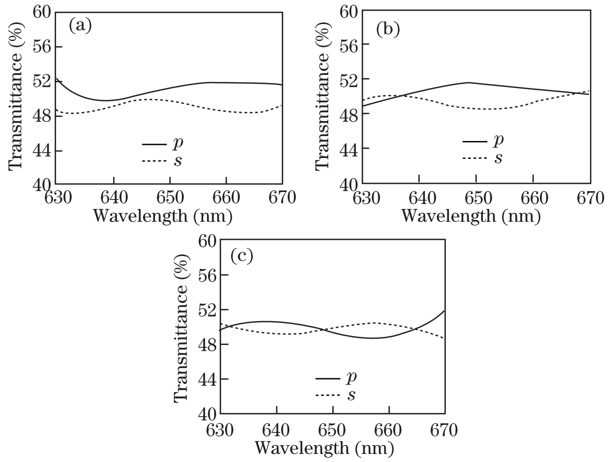

Fig. 3. Reflectance cure at wavelength range of 630–670 nm with different incident angle of (a) 40°, (b) 45°, and (c) 50°.

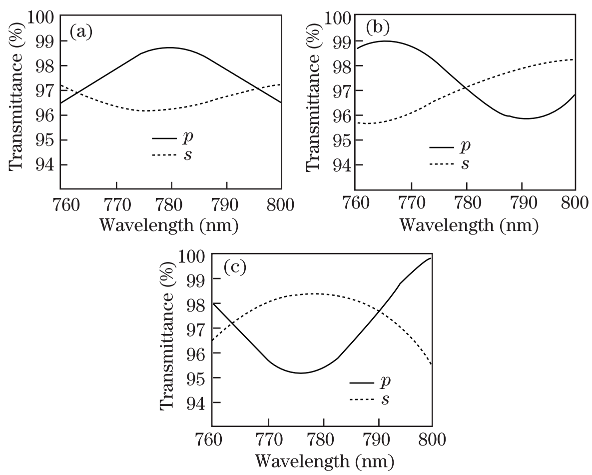

Fig. 4. Reflectance cure in wavelength range of 760–800 nm with different incident angle of (a) 40°, (b) 45°, and (c) 50°.

In conclusion, when used at oblique incidence, optical thin film exhibits polarized-dependent properties. It is an inherent property to single layer, but its' distortions in the polarization state of the incident light can be decreased to some extent by using multilayer structure with appropriate material combination. In this letter, we choose three dielectric thin film material MgF_2, Al_2O_3, and TiO_2, and constitute a thin film stack system with the key pattern of four-layer structure MLMH and two matching layers. After optimization, the reflectance curve of this thin film structure shows that it can control the polarization deviation at two wavelength range of 630–670 and 760–800 nm with incident angle of 40–50°. The design have no losses, and it can work availablity within a reasonable range for both wavelength and angle fields.

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