Wideband film polarizer design

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The reflection and transmittance of s- and p-polarized lights should be treated separately at nonzero angle incidence. By choosing two special film materials whose refractive indices meet the Brewster condition in a given incident angle, the reflection of p-polarized light can be eliminated. When the two materials are fabricated into multilayer stacks, the reflection of s-polarized light can be largely increased while the reflection of p-polarized light keeps low. According to this principle, a film polarizer with bandwidth of 198 nm or even more is designed.

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Thin-film polarizers are widely used in varies of optical fields and play an important role in optical devices. Their characteristics have attracted a lot of research to focus on these films[1−6]. Interference film polarizers[1−3] consisting of a system of multilayer dielectric thin films and basing on the preferential transmittance of p-polarized light at oblique incidence angle have been widely used. However, these polarizers are designed for a particular wavelength and thus have a very limited bandwidth. Film polarizers based on Brewster angle phenomenon which immerses in crystal or liquid increase the spectral region[4−6], but their complicated structures limit their applications.

In this Letter, a new kind of Brewster angle film polarizer is designed by using two super-low refractive index materials. The polarizer is based on Brewster angle phenomenon and is exposed in air instead of being immersed in crystal or liquid. It combines the advantages of both traditional film polarizers, and results in a relative wider band and a simple structure. To our knowledge, there are a lot of methods to deposit film with low refractive index, such as electrochemical etching[7], sub-wavelength structured (SWS) surface[8], and glancing angle deposition (GLAD)[9−11]. Among them, GLAD can be used to fabricate films with the refractive index close to 1, and this method is a potential way to fabricate the proposed Brewster angle film polarizers.

It is known that when light incident on the film with an oblique angle θ, the s- and p-polarized lights should be treated separately. According to fresnel function, the reflections of s- and p-polarized lights at the interface are:

$$R_{\mathrm{s}} = \left(\frac{n_{\mathrm{H}}\cos\theta_{\mathrm{H}} - n_{\mathrm{L}}\cos\theta_{\mathrm{L}}}{n_{\mathrm{H}}\cos\theta_{\mathrm{H}} + n_{\mathrm{L}}\cos\theta_{\mathrm{L}}}\right)^2, \tag{1}$$

$$R_{\mathrm{p}} = \left(\frac{n_{\mathrm{H}}/\cos\theta_{\mathrm{H}} - n_{\mathrm{L}}/\cos\theta_{\mathrm{L}}}{n_{\mathrm{H}}/\cos\theta_{\mathrm{H}} + n_{\mathrm{L}}/\cos\theta_{\mathrm{L}}}\right)^2, \tag{2}$$

where the suffixes s and p denote the s- and p-polarized light, H and L denote the materials with high and low refractive indices at the interface, respectively. If the refractive indices and the incidence angle meet Brewster condition:

$$\frac{n_{\mathrm{H}}}{\cos\theta_{\mathrm{H}}} = \frac{n_{\mathrm{L}}}{\cos\theta_{\mathrm{L}}}, \tag{3}$$

the reflection of the p-polarized light at the interface can be eliminated.

According to Snell's law, the refraction angles and the films' refractive indices satisfy the equation:

$$n_0\sin\theta_0 = n_{\mathrm{H}}\sin\theta_{\mathrm{H}} = n_{\mathrm{L}}\sin\theta_{\mathrm{L}}, \tag{4}$$

where the suffix 0 denotes the incidence material air. To satisfy Eqs. (3) and (4), we require:

$$\frac{1}{(\sin\theta_0)^2} = \frac{n_0^2}{n_{\mathrm{H}}^2} + \frac{n_0^2}{n_{\mathrm{L}}^2}. \tag{5}$$

when Eq. (5) is satisfied, the reflection of the p-polarized light vanishes when light incidents at θ_0, and according to Eq. (2), the s-polarized light is partially reflected. When the two materials are deposited into multilayer stacks, the reflection of the s-polarized light can be largely increased, while the reflection of the p-polarized light keeps low.

To design the Brewster angle film polarizer, the film materials which satisfy Eq. (5) should be chosen firstly. For the nature film materials that exit in the world, the value of $\sin\theta_0$ should be larger than 1. However, there is no nature film material which can be used to fabricate the Brewster angle film polarizer. If the n_{H} and n_{L} decrease to certain values, the value of $\sin\theta_0$ can be smaller than 1, then this kind of wideband Brewster angle film polarizers can be designed and fabricated by two super-low refractive index materials which can be deposited by some special techniques[7−10].

Any point in Fig. 1 represents two material indices n_{H} and n_{L}, and each point below the curve of 90° incidence has a corresponding incidence angle which satisfies Eq. (5), and the two refractive index materials can be used to design the Brewster angle film polarizer. The refractive index relationships with incidence angle of 60°, 70°, 80°, and 90° are illustrated in Fig. 1. In this letter,

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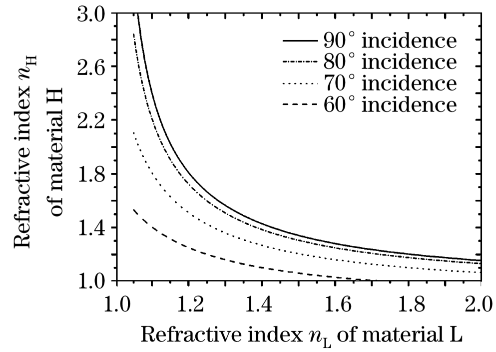

Fig. 1. Refractive index relationship of the wideband polarizer, any point below the curve of 90° incidence can be used to design the wideband polarizer.

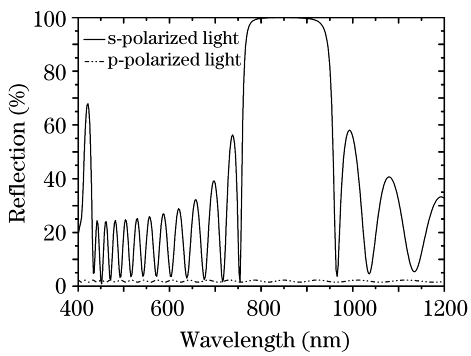

Fig. 2. s- and p-polarized light reflection spectra of the film S/(HL)^12H/A.

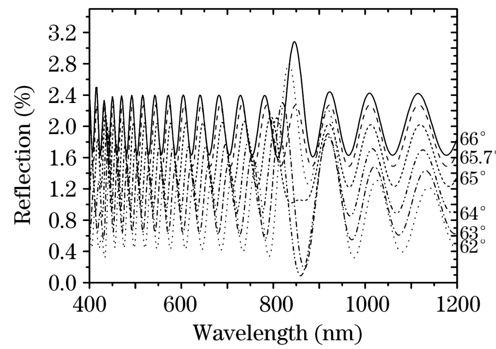

Fig. 3. Reflection spectra of the p-polarized light at different angles, the 65.7° is the Brewster angle of the film materials.

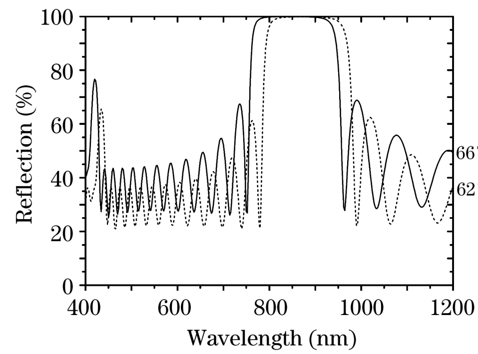

Fig. 4. s-polarized light reflection spectra shift with different incidence angles.

refractive indices 1.4 and 1.2 are used to design the polarizer, and their Brewster angle is 65.7°. The film is constructed of 25 quarter-wavelayers which can be presented by S/(HL)^12H/A, where S presents the substrate of borosilicate (BK7) glass, A presents the incidence media (air), H and L present quarter-wavelayer of the material with refractive indices of 1.4 and 1.2, respectively, and the reference wavelength is 1200 nm. The film's reflection spectra for s- and p-polarized light at Brewster angle are plotted in Fig. 2. The reflection of the p-polarized light is very low for all the wavelength, its value varies from 1.48% to 2.27%, which is caused by the reflections between interfaces of S/H and H/A which do not satisfy the Brewster condition. The reflection of the s-polarized light is higher than 99.6% for the wavelengths from 800 to 900 nm. The full-width at half maximum (FWHM) of the film which transmits p-polarized light and reflects s-polarized light is 198 nm. Compared with the traditional interference film polarizer whose bandwidth is only about 30 nm, this new film polarizer has a wider polarized-band. However, the polarizer's bandwidth can even be enlarged by changing the design. By adding other periodic film stacks to the original design, the film S/1.2(HL)^12(HL)^12H/A has a FWHM of about 400 nm.

Although there are no reflections at the interfaces of H/L and L/H when light incidents at the Brewster angle θ_0, there are still some residual reflections at the interfaces of S/H and H/A, as shown in Fig. 2. This residual reflection determines the p-light's transmittance and the film's optical performance. According to fresnel function, the residual reflection is a function of the incidence angle θ_0, the refractive indices of the film materials, and the thickness of the film. To get the biggest p-light transmittance, considering the residual reflection and the reflections at the H/L interfaces, the angle which yields the lowest p-light reflection should be modified and recalculated. The p-polarized light's reflection spectra of the design S/(HL) 12H/A with different incidence angles are shown in Fig. 3. It is found that if the incidence angle is larger than θ_0, the p-polarized light's reflection in the band which owns high reflection for s-polarized light will increase; if the incidence angle is lower than θ_0, the p-polarized light's reflection in the same band will decrease at the beginning and then increase with the incidence angle decreasing further. For the design of S/(HL)^12H/A, the incidence angle of 64° yields the lowest reflection for p-polarized light in the band which owns high reflection for s-polarized light and the angle is lower than Brewster angle θ_0 (65.7°).

For the s-polarized light, when the incidence angle changes, the reflection spectrum will also change. The reflection spectrum will shift to longer wavelength with the decrease of incidence angle, and the reflection in the band which owns high reflection almost keeps the same and closes to 100%, as shown in Fig. 4. According to Figs. 3 and 4, it is found that the design S/(HL)^12H/A has a work incidence angle band from 62° to 66°, and the incidence angle of 64° yields the lowest reflection for p-polarized light and high reflection for s-polarized light.

In conclusion, a new kind of wideband Brewster angle polarizer is designed by two super-low refractive indices. This kind of polarizer combines the advantages of the two traditional film polarizers, and results in a simple structure and a relative wider band. For this kind of polarizer to get the lowest reflection for p-polarized light, the work angle is not the Brewster angle θ_0 but should be modified and recalculated. Besides, the materials with super-low refractive indices can be fabricated by some special methods like GLAD, and this kind of Brewster angle polarizers will be fabricated in future.

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