Design of large acceptance angle polarizing beam splitter for laser-based displays*

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The performance of broadband polarizing beam splitters (PBSs) is sensitive to the incident angle. By taking account of the spectrum of the laser source and using the needle optimization method, a large acceptance angle PBS for laser-based displays is designed. The average degrees of polarization in transmission and reflection can reach 0.989 and 0.980 for an acceptance angle of 13.6° in air using two materials, while better results of 0.993 and 0.989 for an acceptance angle of 14.8° in air are attained when three common materials are used. Both designs consist of 40 layers.

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Recently, developments in compact and efficient visible lasers are expected to give momentum to the development of laser-based displays for the consumer market[1-4]. Polarizing beam splitters (PBSs) play an important role in display systems for the modulation of polarized light. The PBS has strong angular dependency, which decreases the contrast for low *f*-number illumination[5].

Li[6] proposed a method for the design of broadband and wide angle PBS, and the Brewster angle condition was still necessary. After that Li[7] designed a new PBS with a wide acceptance angle and high extinction, but the PBS is hard to be fabricated. Mouchart[8] and Baumeister[9] designed a large acceptance angle PBSs for a single laser wavelength. In this letter, the spectrum of the monochromatic light source is taken into account for the design, and a more powerful optimization technology is introduced into the design process. A PBS operating in a large angular field for RGB lasers is designed. Two materials satisfying Brewster angle condition are enough to achieve the purpose, and three common materials which don' t satisfy the Brewster angle condition can obtain a better result. These PBSs are more suitable for laser-based displays.

A typical device of MacNeille PBS[10] consists of multilayer of two different coating materials embedded between two prisms. The two diagonal faces are cemented together, and the light is incident upon the hypotenuse. It is known that for oblique incidence, calculations of a multilayer optical film, p-polarized waves and s-polarized waves can be treated quite independently. A tilted optical admittance *h* should be involved instead of that for normal incidence:

$$\eta_p = n/\cos\theta \quad \text{(for p-waves)}, \tag{1}$$

$$\eta_s = n\cos\theta \quad \text{(for s-waves)}, \tag{2}$$

where θ in different materials is given by Snell's law:

$$n_H \sin\theta_H = n_L \sin\theta_L = n_{sub} \sin\theta_{sub}, \tag{3}$$

where H, L and sub represent high refractive index material, low refractive index material, and substrate material, respectively.

It is possible to find an angle of incidence and proper materials so that the Brewster condition for an interface between two materials with different refractive indices is satisfied:

$$n_H/\cos\theta_H = n_L/\cos\theta_L . \tag{4}$$

At this time, the reflectance for the p-polarized wave vanishes. In display applications, the condition θ_{sub}=45° is often met. Combining Eq.(3) and Eq.(4), we obtain[11]

$$n_{sub}^2 = 2n_H^2 n_L^2/(n_H^2 + n_L^2) . \tag{5}$$

To increase the reflectance of s-polarized waves, the two materials should be made into a multilayer stack. The layer thickness should be quarter-wave optical thickness at the angle of

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incidence, so the multilayer stack acts as a multilayer high-reflectance mirror for s-polarized waves. For s-polarized waves, the width of the reflective zone is a function of the tilted optical admittance ratio between the two materials, and the zone can be extended by placing a quarter-wave stack for one wavelength on top of another for a different wavelength, or using a chirped multilayer structure. To evaluate the performance of a PBS, the degree of polarization in transmission is given by

$$P_T = (T_p - T_s)/(T_p + T_s) \ , \tag{6}$$

and that in reflection by

$$P_R = (R_s - R_p)/(R_s + R_p) \ , \tag{7}$$

where T_p, T_s are the transmittances and R_p, R_s are the reflectances for p- and s-polarized waves, respectively.

Compared with polarizers made on plane of glasses[12,13], MacNeille PBS has a much wider spectral range. Unfortunately, it does suffer from a limited angular field. It is simply because when the angle of incidence moves away from the designed angle, Eq.(4) is no longer satisfied, and the multilayer structure acts as a stack with different materials for p-polarized waves. Thus the multilayer stack is approximately equivalent to a reflective coating composite of materials which have small refractive index difference. Therefore, a residual reflectance peak for p-polarized waves gradually appears in the center of the range as the incidence angle moves away.

Fig.1 shows the calculated performance of a MacNeille PBS designed at an incident angle of 45°[8]. This kind of PBS has a wide spectral range which is not necessary for laser-based displays. The residual reflectance of p-polarized waves greatly reduces the degree of polarization in reflection, and thus limits the performance.

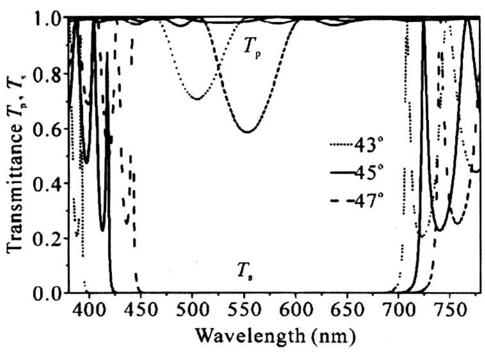

Fig.1 Theoretical performance of a typical MacNeille PBS designed at an incident angle of 45°

For laser-based display systems, the illumination sources are often composed of red, green and blue lasers. Only the spectral characteristics near certain wavelengths have real influence on the performance because of the monochromaticity of lasers. Thus more degree of freedom can be obtained in the design of the thin film devices for laser-based displays. To solve the problem of limited angular acceptance angle, the spectrum of the illumination source is taken into account. On the other hand, targets specified simultaneously for both s- and p-polarised waves set high requirements for optimization method, and classical optimization methods which have local convergence can hardly provide an efficient result. A more powerful optimization technology should be introduced into the design process.

Three laser wavelengths are chosen to make a compromise between color gamut and luminous efficiency: 450 nm for blue, 532 nm for green and 635 nm for red. We get the starting design from an optimized multilayer coating consisting of two materials. The sequence of the staring design is set to Sub/(HL)^13H/Sub. Sub represents the substrate of glass, and H or L denotes a quarter-wave layer of the material with high or low refractive index, respectively.

The method to solve our problem is based on a nonlocal synthesis design technique, i.e., the needle optimization technique[14,15]. For a multilayer optical coating, the spectral performance can be obtained from calculating the characteristic matrix. The difference between the actual and desired spectral characteristics of the design is measured by the merit function (MF). Thus the design problem of optical coating can be taken as an optimization problem. For our problem, the merit function is specified to be T_p=100% and T_s= 0, 435-465 nm, 517-547 nm, and 620-650 nm for five angles of 41°, 43°, 45°, 47°, and 51°. The tolerance is set to be 1%, and 50 spectral points logarithmically distributed are introduced in every band.

The merit function can be decreased by inserting new thin layers into the existing multilayer stack. The variations of the refractive-index profiles caused by such insertions are called as needle variations. Consider a single needle variation of the refractive-index profile after insertion at a physical thickness z inside the existing multilayer structure. The variation of the merit function dMF can be represented as a series with respect to the thickness of a new layer

$$dMF = P(n, z)d + o(d) \ , \tag{8}$$

where d and n denote the thickness and the refractive index of a new layer, and $o(d)$ denotes all terms with an order of d^2 and higher. If $P(n, z)$ is negative, dMF will be also negative, indicating that the merit function can be decreased after the needle variation of specific material at a specific position. $P(n, z)$ is derived by means of variational analysis and is referred as P-function. The P-function is used to identify the most appropriate position to insert new layers. The best decreasing of the merit function corresponds to the lowest negative value of P-function.

The schematic diagram of the optimization procedure is shown in Fig.2.

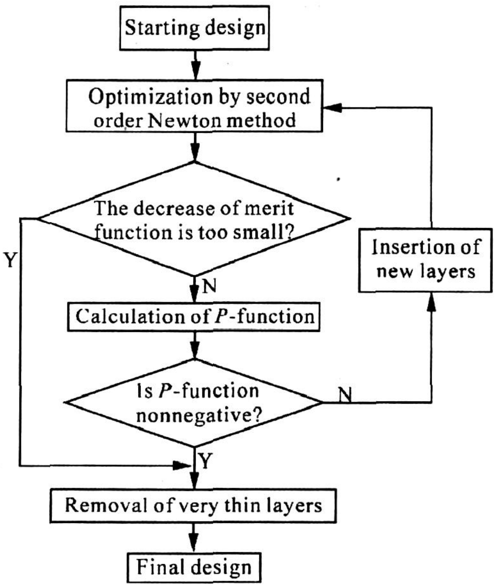

Fig.2 Scheme of the procedure based on the needle optimization technique

An efficient design can be obtained after the previous cycle process is finished. However, this designed coating often contains a relatively great number of thin layers. To get a preferable design, very thin layers (thickness<10 nm) are removed and the structure is reoptimized by the same local optimization algorithm. Generally, the merit function will increase slightly after removing very thin layers, but the number of layers may decrease dramatically and the final design is more suitable to be fabricated.

First, two coating materials are used to design the PBS. The substrate is chosen as a glass with refractive index of 1.7, and the indices of the materials are 1.45 (n_L) and 2.2 (n_H), respectively. The refractive indices satisfy the Brewster angle condition at q_{sub}=45°. Fig.3(a) is the calculated transmittance for p- and s-polarized waves from 400 nm to 700 nm for angles of incidence of q=45°, 45±2°, and 45±4°, respectively. The angular behavior at the lasing wavelength is shown in Fig.3(b). The total physical thickness of the design is about 3.9 μm. Angle q is measured in the glass prism. For a glass prism with index of 1.7, this corresponds to an angular field of 13.6° in air. The value of the merit function is 1.18. Because the merit function is specified in three bands, the residual reflectance of p-polarized light is obvious at other wavelengths. However, this residual reflectance has nothing to do with the performance if the PBS is used for laser-based displays.

Tab.1 shows the average degrees of polarization in trans-

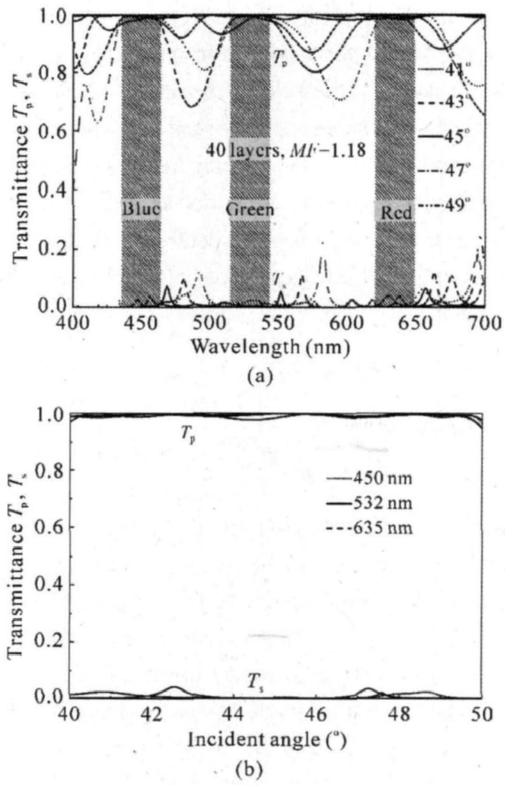

Fig.3 Large acceptance angle polarizing beam splitter for laser-based displays, using two coating materials: (a) Variation of the spectral properties with angle; (b) T_p and T_s as a function of the incident angle in glass for three wavelengths

Eq.(6) and Eq.(7). The average degrees of polarization in transmission and reflection for three bands with different angles shown in Fig.3(a) are calculated to be 0.989 and 0.980, respectively.

Tab.1 Average degrees of polarization in transmission (*T*) and reflection(*R*) for the design using two materials

Incident angle in glass (°)	Blue (435-465 nm)		Green (517-547 nm)		Red (620-650 nm)	
	T	*R*	*T*	*R*	*T*	*R*
41	0.999	0.978	0.971	0.985	0.987	0.976
43	0.996	0.983	0.989	0.981	0.971	0.973
45	0.992	0.993	0.997	0.992	0.995	0.974
47	0.982	0.971	0.994	0.965	0.981	0.975
49	0.988	0.979	0.996	0.981	0.994	0.989

In practice, the materials which satisfy the Brewster angle condition are not easy to find, and the optical constants of the materials have relation with the deposition conditions. So a system which involves more than two common coating materials is required. Another system is designed with three materials. The indices of the materials are: n_L=1.45, n_M=1.67 and n_H=2.3. They are chosen to be close to the refractive indices of SiO_2, Al_2O_3, and Nb_2O_5, respectively. Higher refractive index prisms (ZF7 glass, n_{sub}=1.85) are used as the substrate to get a larger angular field in air. In order to compare with the characteristics of the previous design using two proper materials, this design is adjusted to have 40 layers, too. The calculated performance and the refractive index profile of the resulting design are shown in Fig.4. The total thickness is about 3 μm, which is 77% of the previous design. The value of merit function is further reduced to 0.66, which is 56% of the previous design.

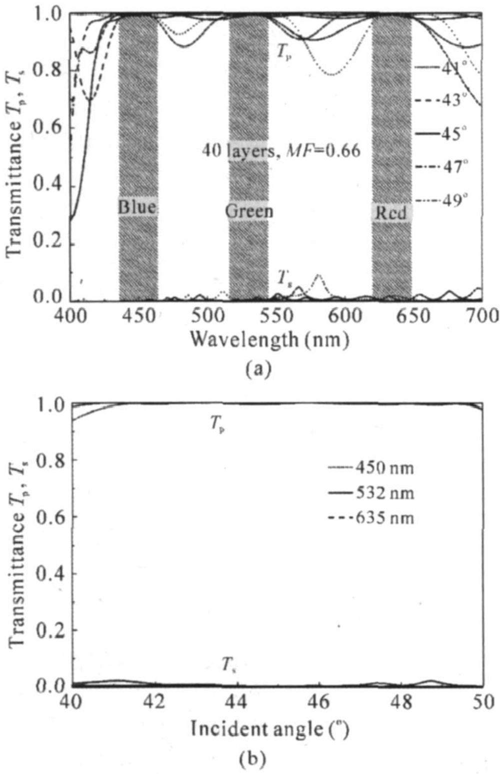

Fig.4 Large acceptance angle polarizing beam splitter for laser-based displays using three common coating materials: (a) Variation of the spectral properties with angle; (b) T_p and T_s as a function of the incident angle in glass for three wavelengths

Tab.2 shows the average degrees of polarization in transmission and reflection for different colors. Compared with the previous design, the degree of polarization for both directions is improved. The average degrees of polarization in transmission and reflection for three bands with different angles are calculated to be 0.993 and 0.989, respectively. In this system, ±4° variation in angle of incidence corresponds to an angular field of 14.8° in air.

Tab.2 Average degrees of polarization in transmission (*T*) and reflection(*R*) for the design using three materials

Incident angle in glass (°)	Blue (435-465 nm)		Green (517-547 nm)		Red (620-650 nm)	
	T	*R*	*T*	*R*	*T*	*R*
41	0.999	0.984	0.988	0.991	0.974	0.984
43	0.999	0.985	0.990	0.990	0.992	0.992
45	0.998	0.992	0.994	0.991	0.998	0.989
47	0.996	0.994	0.992	0.987	0.995	0.992
49	0.999	0.985	0.994	0.989	0.986	0.989

In conclusion, polarizing beam splitters for laser-based displays are designed. This kind of PBS has much better angular performance since the monochromaticity of lasers is considered. The design method is based on the spectrum of the laser source and the needle optimization technique which aims to achieve a nonlocal convergence. Large acceptance angle and high degree of polarization for both the reflection and transmission are obtained using only two or three materials. The average degrees of polarization in transmission and reflection for an acceptance angle of 13.6° in air are calculated to be 0.989 and 0.980, respectively, using two materials which satisfy the Brewster angle condition. Better results of 0.993 and 0.989 are attained when three common materials which don' t have to satisfy the Brewster angle condition are valid, and the acceptance angle is extended to 14.8° in air. The same idea can be applied in design of other thin-film all-dielectric components for laser-based displays.

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