Design of ZnS-Ag color filters for white LED display

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Color filters used in white light-emitting diode (LED) displays are composed of alternating high-index ZnS and metallic Ag layers. Such a filter has low polarization or angle effect. If this filter is used in the case of oblique incident or large cone angles, the wavelength shift can be reduced significantly, and good filter characteristics can be maintained. Therefore, these filters can meet the needs of white LED color displays.

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Fabry-Perot interference filter (FPF), which possesses a region of transmission bounded on either side by regions of rejection, is the simplest and commonest interference filter[1,2]. There are many structures derived from the basic FPF, including the metal interference filter, metal-dielectric filter, and all-dielectric filter or the single-cavity, twin-cavity, multi-cavity, and induced-transmission filter. All these filters are based on the same theory: that interference through multi-reflection in the spacer layers of FPF can strengthen or weaken the magnitudes, depending on the wavelengths, to achieve its filtering effect. Unfortunately, all filters based on FPF principle have a common critical defect: they cannot be used in situations with large angle incident or large cone angles; otherwise the filter characteristics will distinctly deteriorate. This is called polarization effect or angle effect. However, in reality, filters are always exposed to both situations, making them inefficient and, sometimes, even unavailable. For example, white light-emitting diode (LED) displays need stability of wavelength in the case of oblique incident or large cone angle. In addition, for more rigorous optical communications, the effect of filter polarization mode dispersion (PMD) needs to be effectively inhibited[3].

In this letter, we present a novel bandpass filter that is not based on the typical principles of FPF. It is a coating composed of alternating layers of high-index dielectric ZnS and metallic Ag. In order to achieve good filter performance, the number of layers is usually set at seven, and the thicknesses of the two high-index dielectric layers in the center of structure are set higher than the two outer layers. This filter is based on the theory that light is transmittance-induced at certain wavelengths, and rejected at other wavelengths, by metal layers. By applying this structure, the filter can effectively reduce the shift in the central wavelength and maintain satisfactory filter characteristics, even at large incident angles or large illumination cone angles. This is mainly done by avoiding low-index materials that are sensitive to angle effects.

Three designs for the primary colors, blue (B), green (G), and red (R), are listed in Table 1. To meet satisfactory color fidelity, the central wavelengths of the filters for B, G, and R are set at 460, 540, and 620 nm, respectively. In Table 1, Sub denotes substrate of BK_7, A denotes air, λ_0 represents the central wavelength or peak wavelength, and λ_m is the monitoring wavelength. The refractive indices of ZnS and Ag are shown in Table 2. Calculated transmittance curves at wavelengths from 380 to 780 nm for the three designs corresponding to BGR colors are listed in Table 1.

The color filters for a white LED display are usually used at normal incidence but with a cone angle of approximately 36°, which is caused by the total reflection angle in the LED. To compare the properties of the novel filter structure at cone angles of 0° and 36°, we introduce T_{max} to denote peak transmittance and $\Delta\lambda$ to denote half-spectral width, which is the width of the band

Table 1. Structure Parameters of the B, G, and R Color Filters

Design		Sub	ZnS	Ag	ZnS	Ag	ZnS	Ag	ZnS	A	λ_0	λ_m
Thickness (nm)	B		39.4	25.1	242.0	54.2	141.6	28.1	0.0		460	460.7
	G		46.5	31.0	184.3	57.0	184.8	36.0	41.5		540	540.5
	R		196.3	26.1	222.9	54.1	356.7	36.1	183.3		620	618.4

Table 2. Refractive Indices of ZnS and Ag Layers in the Visible Region

λ (nm)	350	400	450	500	550	600	650	700	750	800
n_{ZnS}	2.693-i 0.161	2.541-i 0.01	2.436	2.385	2.356	2.331	2.305	2.288	2.270	2.258
n_{Ag}	0.1-i 3.38	0.075-i 1.93	0.055-i 2.42	0.050-i 2.87	0.055-i 3.32	0.060-i 3.75	0.070-i 4.2	0.075-i 4.62	0.080-i 5.05	0.090-i 5.45

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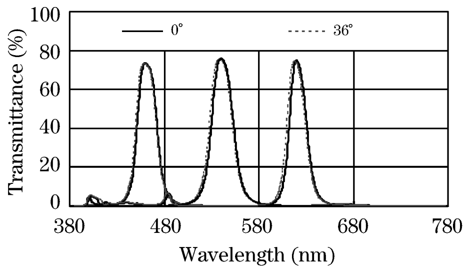

Fig. 1. Calculated transmittance curves of three colors listed in Table 1.

Table 3. Calculated Properties of B, G, and R Filters at Cone Angles of 0° and 36°

Filter	Cone Angle of 0°			Cone Angle of 36°		
	λ_0 (nm)	T_{max} (%)	$\Delta\lambda$ (nm)	λ_0 (nm)	T_{max} (%)	$\Delta\lambda$ (nm)
B	460	73.3	22.7	458.9	72.9	22.7
G	540	75.8	25.0	538.6	75.6	25.1
R	620	74.8	20.0	618.1	74.2	20.2

measured at half of the peak transmission. The calculation results of the three color filters for cone angles of 0° and 36° are shown in Fig. 1 and listed in Table 3.

Figure 1 and Table 3 show that the filters have close characteristics for both 0° and 36° cone angles. By using this novel structure, the cone angle effect of color filters can be ignored. It means that even in the case of large cone angles, shift of the central wavelength can be avoided, and the performance of the filter can still be maintained in order to meet the requirements of white LED display. This is totally different with that of FPF.

Color filters are sometimes illuminated not only through cone angles but also through large incident angles. The impacts of both incident angle and cone angle on the green filter characteristics are shown in Fig. 2, where the incident angle is 30° and the cone angle is 36°. Aside from the increase in the incident angle and the cone angle, the central wavelength of the FPF significantly shifts towards a shorter direction. Worse, it reduces the peak transmittance and deteriorates the half-spectral width and rejection at both sides of its peak wavelength. Here, the structure of FPF, which is that of a double half-wave filter, can be expressed as

$$\mathrm{Sub}|\mathrm{HLHLLHLHLHLHLLHLH}|\mathrm{A}, \mathrm{H}-\mathrm{TiO_2}, \\ \mathrm{L}-\mathrm{SiO_2}, \lambda_0 = 540 \text{ nm}.$$

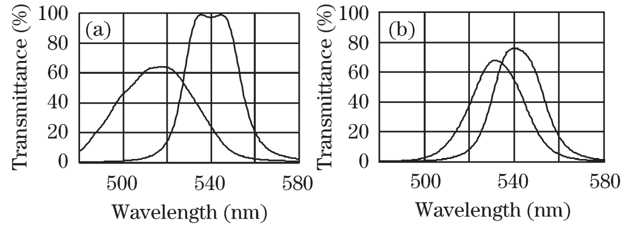

Fig. 2. Effects of 30° incident angle and 36° cone angle in (a) FPF and (b) novel filter on green filter performance.

The refractive indices of TiO_2 and SiO_2 at the wavelength of 550 nm are 2.385 and 1.454, respectively. Although the number of layers of the novel filters was greatly reduced in comparison with FPF, it still had high rejection and tolerable spectral width. Moreover, the secondary transmission band disappears in the short wavelength and long wavelength regions from 380 to 780 nm (Fig. 1), whereas, in FPF, there is still a need for it to be eliminated by auxiliary layers or absorptive glass. The disadvantage of this novel structure is that peak transmittance is lower at normal incidence because of the absorption of Ag layers. Compared with FPF, the novel structure has three main advantages: 1) as incident angle and cone angle increase, the shift of central wavelength toward shortwave is reduced; 2) there is relatively smaller decrease in peak transmittance and increase in spectral half-width, which results in a dramatic reduction of the splitting of s- and p-polarization; and 3) there is a better cut-off performance from 380 to 780 nm. The novel structure still has better filtering performance, even if the incident angle is 45° and cone angle is 36°. On the other hand, FPF is completely deteriorated at these parameters, which means that the filter has lost its practical value.

Calculations also show that the peak wavelength shift of the filter is mainly caused by the incident angle, as demonstrated by the green color filter shown in Table 4. The peak transmittance and half-width of FPF are mainly affected by both the incident angle and the cone angle, but the peak transmittance and half-width of the novel filter are only affected by the incident angle.

In conclusion, the novel filter not only has the advantage of less angle effect compared with traditional FPF, but also has a simple structure and convenient preparation. When the incident angle is 30° and cone angle is 36°, the shift of the central wavelength induced by the angle effect between FPF and novel filter is reduced to approximately 61%. The peak transmittance and spectral

Table 4. Effects of Incident Angle and Cone Angle on Filtering Characteristic of Green Filter

	Incident Angle (°)	Cone Angle (°)	λ_0 (nm)	T_{max} (%)	$\Delta\lambda$ (nm)
FPF	0	0	540.0	98.7	21
	0	36	538.1	75.5	25
	30	36	517.9	64.1	43
Novel Filter	0	0	540.0	75.8	25
	0	36	538.6	75.6	25
	30	36	531.5	67.8	27

half-width changes are reduced to about 77% and 91%, respectively. These results indicate that compared with the traditional FPF, the novel filter does not suffer serious degradation in wavelength shift, peak transmittance, spectral half-width, and rejection. Therefore, these results prove that such novel filters are appropriate for use in white LED displays.

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