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Coating Materials News

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The holiday season brings color to the otherwise drab and colorless winter scene. In this issue we add color as created by thin film coatings. In a previous issue, we demonstrated decorative and selectively colored reflectors based on thin metal films that replicated gold and other colors. The colors produced by designs incorporating semi-transparent layers with different dielectric layer thickness were computed with Macleod's software [1]. Now we present a wider range of colors and demonstrate color spectrum shifting when the angle of incidence on a coating is changed. Colored bands appearing on coating chamber shielding and walls are familiar sights. Decorative and artistic coatings can be created by deliberately controlling coating design and deposition geometry. The creation of thin-film color by interference invokes many of the principles that we have presented in CMN over the years. Geometry as well as layer design plays a significant role in determining the color reflected by an interference coating, as we shall see.

Creating a Color Spectrum

Starting with a reflecting design consisting of QWs and Hws of Titania and Silica films on glass, we tilt it to vary the angle of incidence (aoi) from 0° to 65° and plot the color change again using Macleod's software (Thin Film Center) [2]. The reflectance for P-polarization vs. aois 0°, 30°, and 45° are shown in Figure 1. The illuminating source has a color temperature 5500 K (whitelight), and the analyzed color corresponds to visual photopic response. We demonstrate how the reflection band shifts short-ward as aoi is increased. This is caused by the decreasing path difference that occurs between the interfering reflected rays as aoi is increased. The next plot, figure 2, shows the reflected visual color vs. aoi.

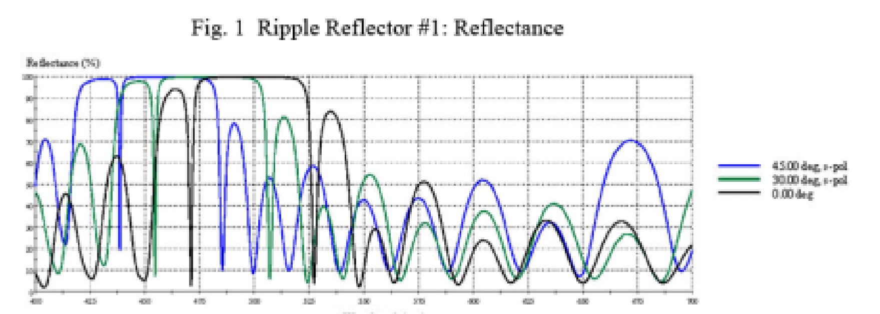

Figure 1. Reflection band spectral position for a QW design at three angles of incidence. (P-polarization).

The color coordinate map shown in the Figure 3 plots the change in visual coordinates X Y chromaticity coordinates vs. aoi 0°-65°. The reflector center wavelength is designed to constrain the reflected colors to be within the visual sensitivity range of the eye as indicated by plot outline. Sources of different color temperature (illuminant spectral content) will alter the color that is perceived.

How can this thin-film interference phenomenon be used? If a transparent substrate is coated at perpendicular incidence and then is bent into a cylindrical shape and illuminated from above as shown below, an observer receiving reflected light from around the cylinder will see the color spectrum spread shown in figure 2.

Figure 2. Visual color spectrum vs. angle of incidence. Red appears at 0° aoi and green at 65° aoi.

The colors in the transmitted beam are the reverse of those in Figure 2. Color saturation is higher for the reflected beams than for the transmitted components. Light component vibrating in the plane of reflection, P-pol, exhibits higher color saturation. This all-dielectric colored reflector design works only on transparent substrates when the transmitted complimentary component is eliminated.

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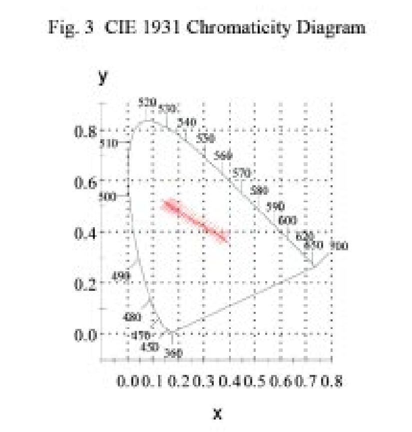

Figure 3. Location of the color coordinates for the QW reflector changes as angle of incidence changes.

While a similar color display would be seen if a cylinder (or sphere) was coated by a line-of-sight deposition distribution (E-beam, for example), the multi-layer film structure is not the same. The layers shown in Figure 4b are parallel and equi-thickness; however the layers deposited on a curved surface (4a) will have thickness and growth structure gradients due to the change in aoi of the depositing vapor stream caused by the curvature. The use of a high-pressure deposition technique, such as sputtering or CVD, both with reduced directivity compared with thermal evaporation will reduce the influence of aoi introduced by the curved substrate geometry. Scatter present in the higher pressure techniques provides more uniform spatial coverage than lower pressure processes such as thermal (e-beam or resistance-heated) evaporation.

Constant Color over a Wide Angle

With clever design of the reflector to produce two reflection bands and materials that have a lower H/L index ratio than the first design, it is possible to create a coating whose color is essentially constant over an aoi range of 0° to 65°. Figure 5 shows the reflected color of such a design and its tight X Y coordinate mapping. Similarly, a nearly constant red reflector can be made simply by changing the design wavelength, see figure 7.

Another Approach: Opaque Substrate Coatings

Results achieved by the multilayer QW reflector designs above can also be achieved with much simpler designs; designs employing semi-transparent metal films and dielectric layers on a nontransparent substrate. Light that is not reflected is absorbed within the coating, therefore metal substrates can be used. While these designs require fewer layers, the thickness and index of the thin metal layers are critical, and subject to reproducibility errors as a result of partial oxidation of the metal. Figure 8 shows the 0° to 65°color.

Color saturation for the metal design is less sensitive to polarization than for the QW design, as shown in figure 9. Because the reflectance curves do not have steep edges as the QW stack does, there is a smaller dependence on polarization. By adding a second reflection band, we can make a reflector whose color grades with aoi, as shown in Figure 10.

Wide Angle Black Coating

For that black coal requirement, a design has been generated that has <2% average reflectance over the visible spectrum. In addition to a stocking stuffer, such a coating has application in display background, optical system baffling, etc. Opaque substrates are used. The advantages over black paint are: no volatile out-gassing, specular only reflection, and sharp edge definition in small features. Unlike paints, the coating exhibits no scatter; the low reflection is created within the film structure by absorption and interference. Figure 11 shows the chromaticity coordinates that indicate a visually neutral color over aoi 0° to 60° that nearly coincides with the neutral point (X).

In this issue, we have demonstrated the control of color over large incidence / observation angles by the use of thin-film coatings. Applications are limited only by the imagination.

Fig. 4

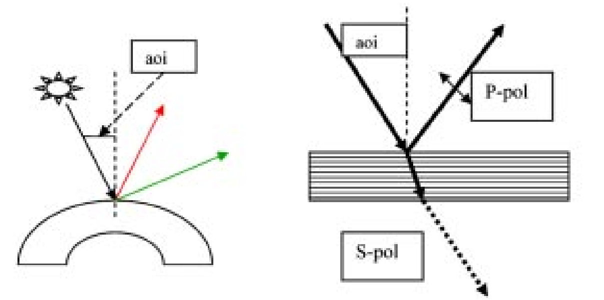

Figure 4. a) The color of the multi-layer coating depends on incident and reflected angles. b). The predominant polarization components exhibit different color saturation: reflected S-polarization is more intensely saturated than refledcted P-pol or the transmitted components.

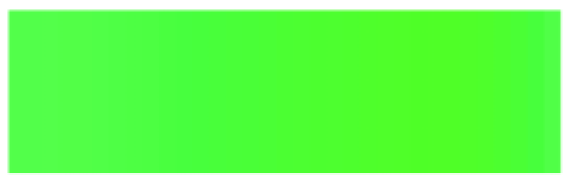

Figure 5. Coating exhibiting nearly invariant green color over angles of incidence 0° to 60°

Fig. 6 CIE 1931 Chromaticity Diagram

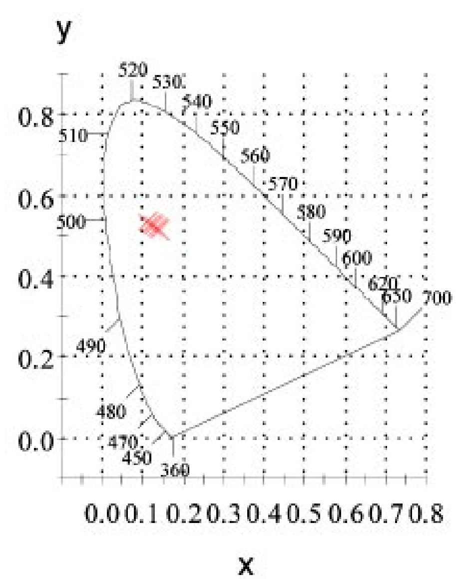

Figure 6. Chromaticity diagram for the angle-invariant green reflector.

Figure 7. Reflection of a coating design over aoi 0° to 65°.

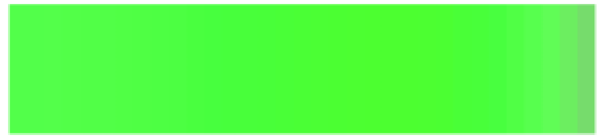

Figure 8. Green color on a metal substrate, covering aoi 0° to 65°.

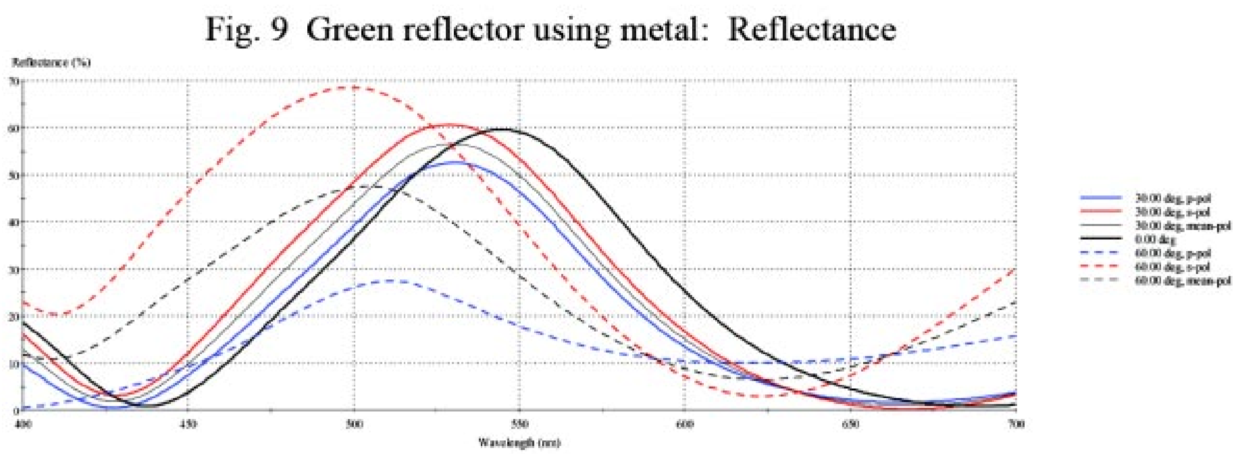

Figure 9. Reflectances for the color reflector design using metals.

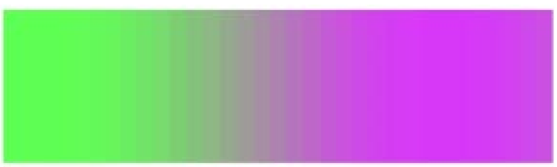

Figure 10. Mean reflectance colors from a metal reflector vs. aoi.

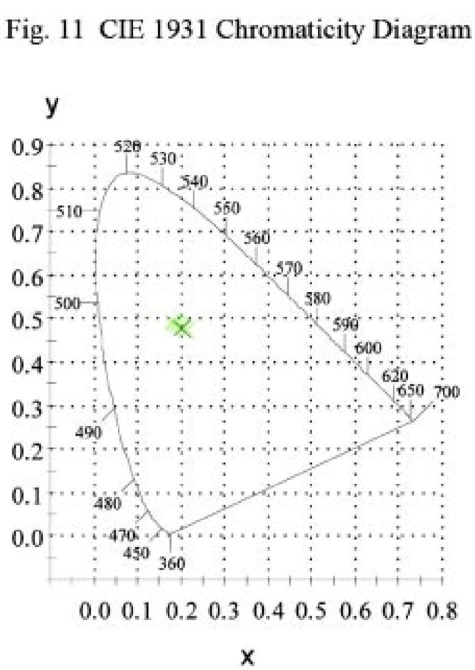

Figure 11. Coordinate map for a black coating over aoi 0° to 60° and mean polarization. X indicates the neutral (white) point.

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2. Essential Macleod. www.thinfilmcenter.com.