Advances in Natural Science
Vol. **3**, No. **2**, **2010**, pp.317-323
www.cscanada.net

ISSN 1715-7862 [PRINT]
ISSN 1715-7870 [ONLINE]
www.cscanada.org

The 3rd International Conference of Bionic Engineering

Influence of the Optical Multi-Film Thickness on the Saturation of the Structural Color Displayed[1]

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Abstract: In this paper, it is demonstrated that saturation of the structure color exhibited by the multi-film systems can be determined by the thickness parameter of the layers of multi-films. To prove this principle, the multi-film of 1-quarter film system and 3-quarter film system with the central wavelength of 650nm, exhibiting a color red, are fabricated by deposition method. Simulation was done base on the light interference principle, and both simulation and experiment results show that the reflective spectra of the 1-quarter film system have a wider bandwidth. Saturations of the color from different systems are calculated separately by the CIE colorimetry method, to prove that the 3-quarter film system produces colors with higher saturation.
Keywords: saturation; structural color; multi-film; thin film thickness; interference principle

1. INTRODUCTION

Multi-film interference principle, as one of the most common cause of structural color in nature (Kinoshita, 2008; Kinoshita & Yoshioka, 2005), has been widely applied to nano-fabrication field. It has been found that certain butterfly wings can cause bright colors according to the interference of the coherent light (Tada et al., 1999). Zhongling Wang's group has demonstrated that the ground scales of Morpho peleides butterfly's

[1] **This work was funded by National Natural Science Foundation of China (No. 50875250).**
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* Received 19 April 2010; accepted 20 July 2010

wings exhibit its shining color due to this principle (DING et al., 2009). With the thriving of structural color, the colors caused by the interference of the multi-films have been studied widely in recent years (TANG et al., 2009; Muller & Sand, 1987). And, the main characters of color require further analysis.

Among all the film systems, 1-quarter film system is a traditional multi-layer thin film system, which is rather advisable due to its advantage of simple (Born & Wolf, 1959). Once a central wavelength is fixed, with the knowledge of the refraction index the two alternative materials, the thickness of a single layer can be obtain. Thus, it is a widely-used system in optical film industry.

2. EXPERIMENT

In order to analyze the influence of the film thickness to the saturation, we introduced a film system in the complemental period of the 1-quarter film system, the 3-quarter film system, to make a comparison. The structure of the 3-quarter film system is exactly like that of the 1-quarter film system, with the optical thickness of each layer three quarters of the aimed reflective wavelength rather than one quarter of the wavelength. The structure of the two kind of multi-film is shown in Fig.1.

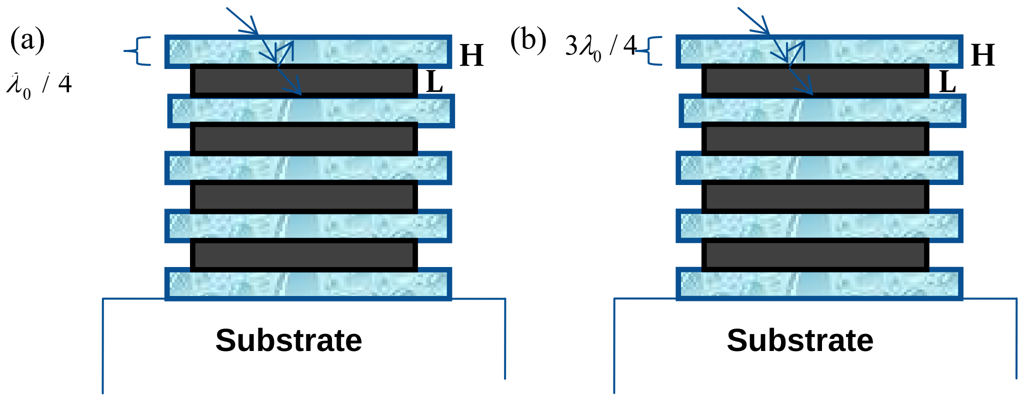


Fig. 1: Scheme of the structure of the two systems (H stands for the layer with higher refraction index; while L stands for the one with lower refraction index): (a) Scheme of the structure of the1-quarter film system (b) Scheme of the structure of the3-quarter film system

The optical thickness of each layer is $3\lambda_0/4$, where λ_0 refers to the wavelength of the incident light. H stands for the layer with higher refraction index; while L stands for the one with lower refraction index. And we chose ZrO_2 as (n=2.0) the layer with higher refraction index, and SiO_2 as the layer with lower refraction index (n=1.46). Flat optical glass is selected as the substrate.

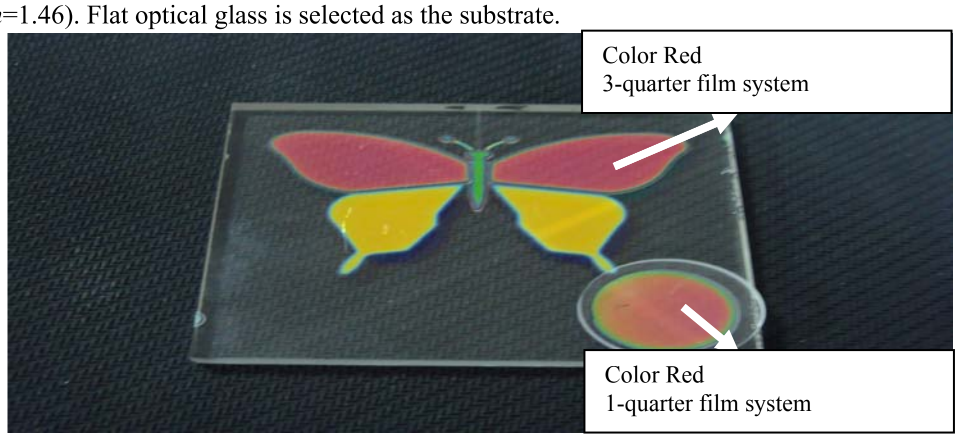


Fig. 2: Samples of the red color with 1-quarter film system (up wing of the butterfly) and 3-quarter film system (round sample below)

Based on the materials chosen above, we designed a multi-film system with the central wavelength of 650nm, which exhibit a color of red. In the deposition process, electron beam evaporation method is used as a supplementary. And fifteen layers were deposited on each substrate altogether. The sample are shown in Fig.2. The color caused by the 3-quarter film system is pure enough for the fabrication of patterns, and all the colors in the butterfly pattern are fabricated according to this principle.

As shown in Fig.2, the red color of the up wing of the butterfly is produced by a 3-quarter film system; while the round sample below showing a shallow red is produced by the traditional 1-quarter film system. Seen from the bear eyes, an obvious difference can be observed. However, further analysis still is required.

3. SIMULATION AND EXPERIMENT RESULTS

The simulations of the two systems were carried out by the FilmStar software. And the results of the two systems are shown in Fig.3. From Fig.3, we can see that the central wavelengths of both systems are all located at 650nm, which fits our design quite well. And the bandwidth of the 3-quarter film system is much narrower than the one of the 1-quarter film system, which fits the vision from bare human eyes.

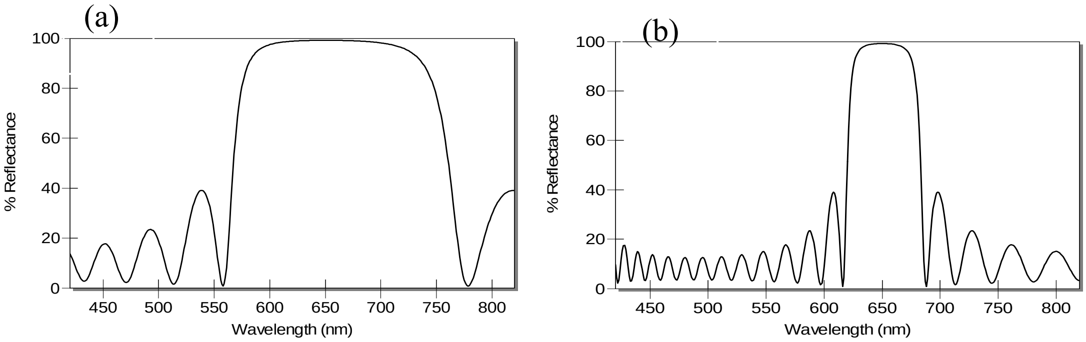
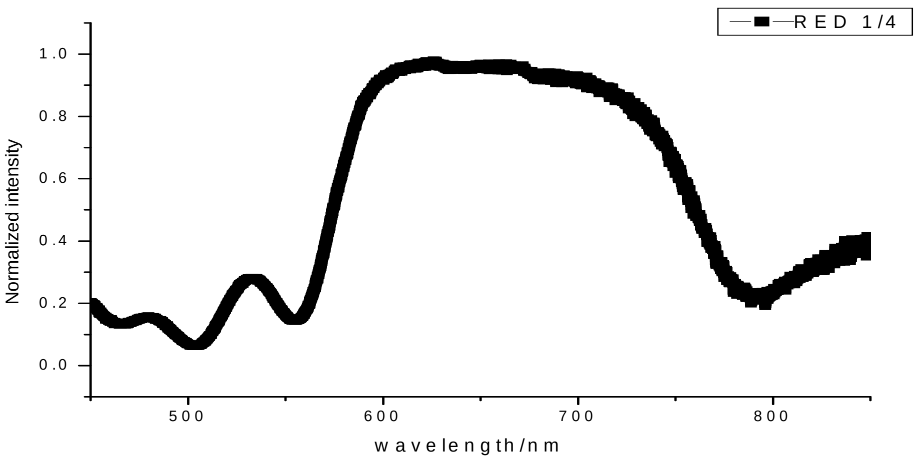
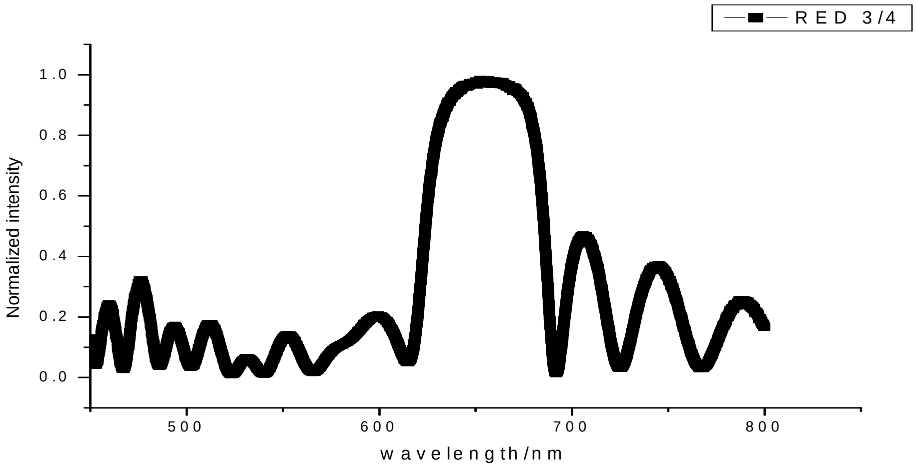


Fig. 3: Simulation results of the reflectance of the two film systems: (a) Simulation result of the 1-quarter film system (b) Simulation result of the 3-quarter film system

The actual reflection spectra shown in Fig.4 were detected by the Raman fluorescent spectrometer, with the light source changed to white light; while the spectra of the light source should be tested as a reference first. And thus the reflective curve can be obtained correctly.



(a) Reflective spectrum of the 1-quarter film system



(b) Reflective spectrum of the 1-quarter film system
Fig. 4: Reflective spectra of the two film systems

As shown in Fig.4 (a), though the central wavelengths are both at 650nm, the curve rises at the wavelength of around 550nm and decreases at about 750nm, with a bandwidth of 200nm. And the simulation results in Fig.3 (a) agree with it exactly. In Fig. 4 (b), the curve rises at the wavelength of around 620nm and decreases at about 690nm, with a bandwidth of 70nm, which agrees with the result in Fig.3 (b).

4. SATURATION

To further characterize the structural color it produced, the colorimetry principle is introduced.

Hue, saturation, and brightness are regarded as the three main aspects of colors in the red, green, and blue (RGB) scheme, determining the properties of colors. Saturation, as one of the most important parameters of color, influences the deepness of the color in vision.

Saturation can be defined as the ratio of the brightness of the monocolor light stimulus to that of the white light stimulus, which can be attributed to the distance between the chromaticity point of the color and the one of non-chromatic stimulus point in the chromaticity diagram (JING & HU, 2006).

The sense of color requires four basic parameters: the light source, the object with color, eyes and brain. The calculation of the three stimulus values *X*, *Y*, *Z* requires the energy distribution of the light source $S(\lambda)$, the reflection character of the sample's surface $R(\lambda)$ and color vision of human eyes. And thus it can be expressed as:

$$\begin{aligned} X &= k\int_{\lambda} R(\lambda)S(\lambda)\overline{x}(\lambda)d\lambda \\ Y &= k\int_{\lambda} R(\lambda)S(\lambda)\overline{y}(\lambda)d\lambda \\ Z &= k\int_{\lambda} R(\lambda)S(\lambda)\overline{z}(\lambda)d\lambda \end{aligned} \tag{1}$$

Where k is the modification factor; the stimulus value Y strands for both the relative quantity of green and the brightness factor of the sample.

The light source is the standard light source D65 (shown in Fig.5), and the reflective spectra have been measured. The color vision of human eyes has already known as Fig.6. So the three stimulus values can be obtained.

According to the definition, we calculate the normalized chromaticity coordinate x, y, z in the equation below, which can be pointed in the chromaticity diagram.

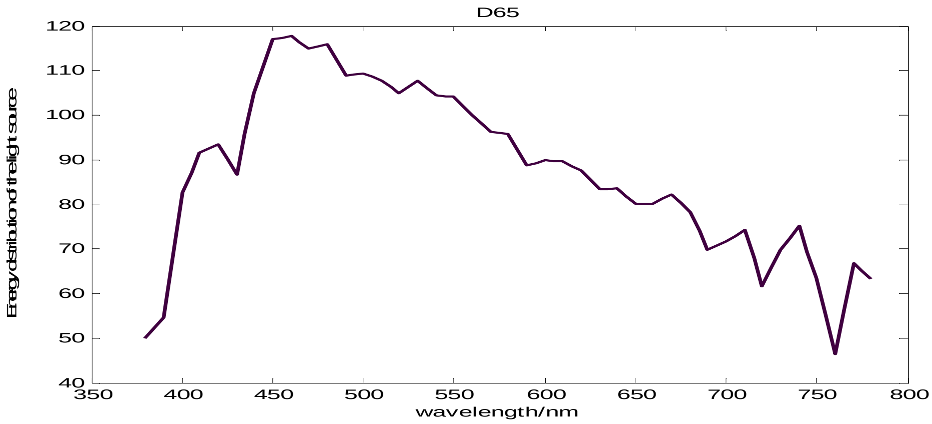


Fig. 5: Energy distribution of the standard light source D65

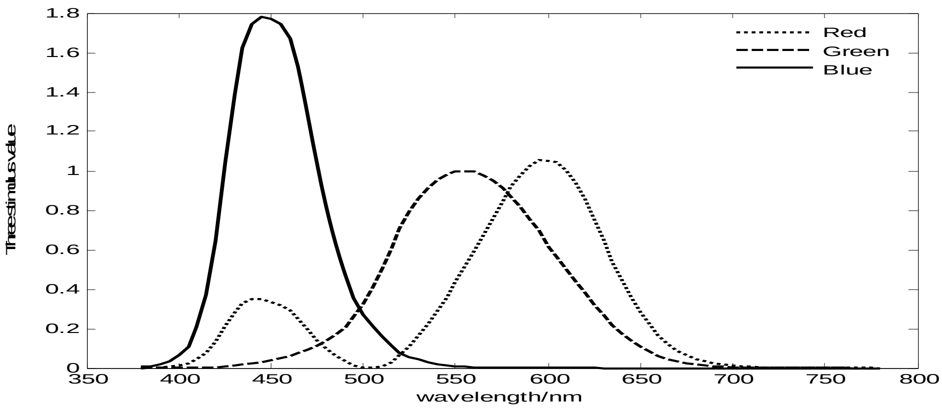


Fig. 6: Three stimulus value curve of the spectra

$$x = \frac{X}{X + Y + Z}$$
$$y = \frac{Y}{X + Y + Z} \qquad (2)$$
$$z = \frac{Z}{X + Y + Z}$$

The x, y values of the 1-quarter film system and the 3-quarter film system are (0.40092, 0.23787) and (0.48565, 0.35113), respectively. It is already known that the coordinate of the non-chromatic stimulus point in the chromaticity diagram is (0.3101, 0.3162). The distance between the point of the systems and the non-chromatic stimulus point can present the saturation of the colors in the chromaticity diagram. The distance between the point of the 1-quarter film system and the non-chromatic stimulus point is 0.1199; while that of the 3-quarter film system and the non-chromatic stimulus point is 0.1790. The value of the 3-quarter film system is larger, which well proved the conclusion that its saturation value is larger than the one of the 1-quarter film system.

5. FURTHER SIMULATION

Further, the simulations of the 5/4λ film system and 7/4λ film system have been carried out. The results are shown in Fig.7.

(a)

(b)

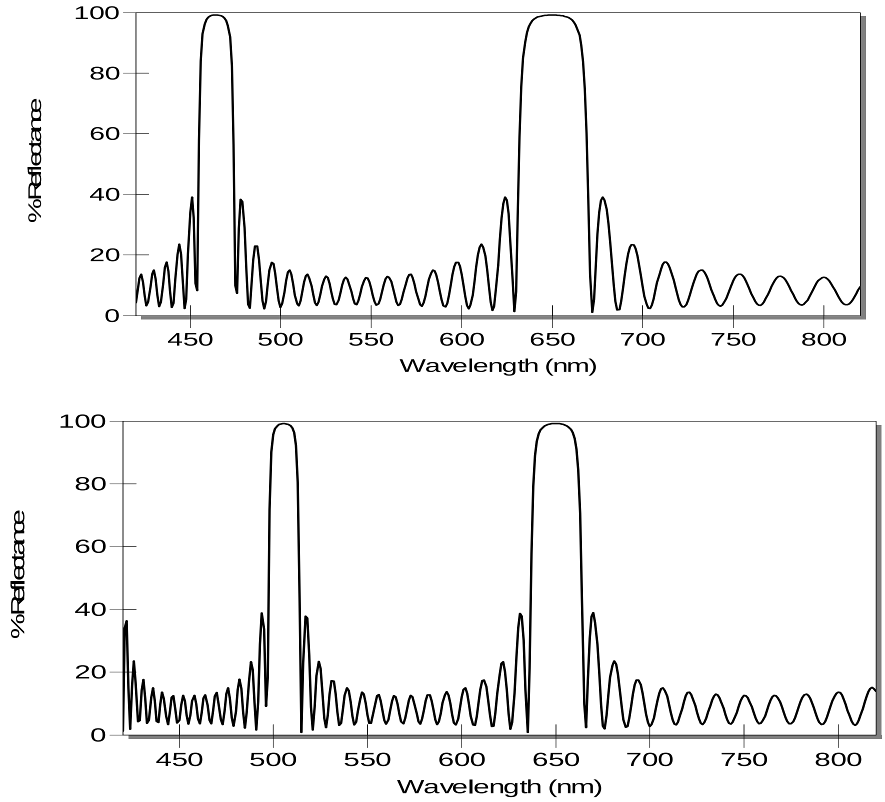


Fig. 7: Simulation results of the reflectance of the two film systems: (a) Simulation result of the 5/4λ film system (b) Simulation result of the 7/4λfilm system

From Fig.7, we can see that the 5/4λ film system (Fig.7 (a)) has a bandwidth of about 50nm; while the 7/4λ film system (Fig.7 (b)) has a bandwidth of 40nm. From the saturation calculation process above, we can reach the conclusion that the 5/4λ film system has higher saturation than the system discussed before, and the 7/4λ film system has the highest saturation of all the four systems. Thus, the thicker of the multi-film layer can obtain a color with higher saturation. However, the 5/4λ film system and the 7/4λ film system will introduce other peaks in visible light range.

6. CONCLUSION

In this paper, two kind of multi-film systems are deposited by electron beam evaporation method. The structural colors of red with the central wavelength of 650nm have been achieved by light interference. From the reflective spectra, saturations of colors caused by the two systems can be obtained by the CIE colorimetry method. Results show that the saturation of the color caused by the 3-quarter film is higher than the one by the 1-quarter film system. Further simulations show that thicker thickness will result in narrower bandwidth in spectra, with interfere peaks introduced too. In conclusion, with other parameters remaining the same, thicker multi-film system can cause the structural color with higher saturation.

REFERENCES

Born M, Wolf E. (1959). *Principles of Optics*. Cambridge University Express.

DING Y, U S and WANG Z. (2009). Structural Colors from Morpho peleides Butterfly Wing Scales. *Journal of Applied Physics. Vol 106(7)*.

JINGW, HU W. (2006). *Radiometric, photometric and colorimetric measurement* (in Chinese). Beijing Institute of Technology Press.

Kinoshita S, Yoshioka S and Miyazaki J. (2008). Physics of structural colors. *Rep. Prog. Phys. 71*, 076401 (30pp).

Kinoshita S, Yoshioka S. (2005). Structural Color in Nature: The Role of Regularity and Irregularity in the Structure. *ChemPhysChem 6*, 1442-1459.

MullerR, Sand M. (1987). Optimum Angle of Incidence for Observing Thin-Film Interference Colors. *Appl Opt*. *Vol 26(24)*. pp: 5211-20.

TadaH, Mann S and Miaoulis et al. (1999). “Effects of a Butterfly Scale Microstructure on the Iridescent Color Observed at Different Angles”. *Optics Express Vol 5(6)*. pp: 87-92.

TANG K, HOU J, ZHANG Q et al. (2009). The Color Display Technology Based on the Thin Film Interference. *2009 Conference on Lasers & Electro Optics & The Pacific Rim Conference on Lasers and Electro-Optics*. Shanghai, China.