Research on Spectral Reflection Characteristics of Nanostructures in Morpho Butterfly Wing Scale

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Abstract. The intricate nanostructure in the scales of Morpho, which is composed of transparent cuticle protein, achieves an extremely high reflectivity in the range of visible light. The brilliant iridescent blue color is not produced by blue pigment but nanostructures. In order to investigate which structural parameters influenced the spectral reflection characteristics and formed the striking brilliance of blue color, a vector diffraction theoretical structural model was established, and simulation using rigorous coupled-wave analysis was carried out. The complex nanostructure was assumed as the diffraction grating structure of arbitrary configuration. The shape and size of the model was set according to the TEM photos of Morpho scale. The structure with irregular asymmetric multilayer lamellae ridge-like grating possessed best capability in reflectivity and color matching. The influence of every structural parameter to spectral reflectivity was cognized by comparing with the original spectrum. The results have revealed the nature of iridescent blue colors and high reflectivity, and enable us to control color and reflectivity by manufacturing nanostructure with specific structural parameter.

Keywords: Morpho butterfly, micro/nano structure, structural color, rigorous coupled-wave analysis.

1. Introduction
Three centuries of research, beginning with Hooke and Newton, have revealed a diversity of structural color at the submicrometre scale in nature [1-2]. Many birds, insects (particularly butterflies and beetles), fishes and lesser-known marine animals exploit structural colors on their surfaces to make their color changed with viewing angle (iridescence) or appear ‘metallic’ [3-7]. A tropical butterfly, Morpho Rhetenor, is famous for structural color. The striking brilliance of the iridescence blue color is so bright that it can reportedly be seen from “a quarter of a mile off” [8]. The blue color is not generated from blue pigment but nanostructures [9]. The intricate nanostructure achieves an extremely high reflection in the short wavelength range of the visible spectrum [10-11]. These optical characters depend strongly on the micro/nano structural properties, such as the 2D-mode, the minimum size, periodicity and type of arrangement [12]. There are many techniques such as FDTD employed to investigate which
structural parameters influenced the spectral reflection characteristics. It is found that the rigorous coupled-wave analysis (RCWA) has a good performance in calculating the sub-wavelength diffractive structures in terms of the vectorial wave diffraction theory. In this paper the complex nanostructure was modeled and simulated by the RCWA.\textsuperscript{[13]}

The rest of the paper is arranged as follows. Section 2 depicts the spectral reflectivity of \textit{Morpho Rhetenor} scales and the experimental optical system. Section 3 describes the nanostructure of \textit{Morpho Rhetenor} and the two-dimensional simulation model. The RCWA algorithm is also introduced briefly in Section 3. The simulation results of different structural parameters are presented in Section 4. Finally, Section 5 comes to the conclusions.

2. Spectral reflectivity of \textit{Morpho Rhetenor}

We worked on a highly iridescent butterfly species, \textit{Morpho Rhetenor}, as shown in Fig.1. Its nanostructures achieved an extremely high reflection, which depended strongly on the wavelength, polarization state, angle of incidence, shape of illuminating wave-front and the index of ambient medium.\textsuperscript{[14-15]}

To measure the reflective spectrum, an optical system was designed (as shown in Fig.2). In the experiments, the light was emitted from a HL-2000 Tungsten Halogen Light Source, went through the optical fiber, and irradiated on the reference plate (WS-1-SL, a white reflectance standard from Labsphere made from Spectralon) or samples. Then the light was reflected, captured by the reflection probe QR400-7-UV/VIS, and inputted into an Ocean Optics HR2000+ spectrometer. Here the high-resolution spectrometer with a response range of 200-1100 nm was employed to capture visible spectra.

![Figure 1. The Morpho Rhetenor butterfly.](image1)

![Figure 2. The schematic diagram of the experimental optical system.](image2)

![Figure 3. Reflective spectrum of Morpho Rhetenor scales.](image3)

Here we only focused on the reflective spectrum of \textit{Morpho Rhetenor} in the visible spectra range from 0.38 to 0.78 μm. As shown in Fig.3, the x-coordinate was wavelength and the Y-coordinate was reflectivity efficiency. It was found the peak was located in the range of 450 ~ 460nm with the value of 83%, which corresponds to blue light. The reflectivity was more than 60% from 448nm to 520nm, that is, the bandwidth was nearly 72nm, which was relevant to homochromatism.

3. Modeling the scale structure

\textit{Morpho Rhetenor} has single layer of scales, as shown in Fig.4a, which contains little pigment. The reflectivity peak of \textit{Morpho Rhetenor} reaches 80%.

It can be found from Fig.4b, the intricate ridges arranged periodically and composed a grating...
structure\textsuperscript{[16-17]}. It was the grating structure who produces the iridescence and high reflectivity\textsuperscript{[18]}. As shown in Fig.4c, the transverse section of ridge was just like a tree with many branches. Each ridge had 11 layers of lamella (the "branches" of the tree-like structure). Lamellas nearly paralleled the base of ridge. The topper lamella was narrow than lower lamella. Ridge and basement were not vertical, but angled.

![a. The OM image of scales b. The SEM image of one scale c. The TEM image of transverse section of one scale.](image)

**Figure 4.** The structure of *Morpho Rhetenor* scale

According to the measurements reported in Vukusic at al\textsuperscript{[19]}, the complex optical index of this tree-like structure would be approximated by the constant value $n = 1.55 + 0.05i$ in the whole optical range. The model had an $x$-invariant structure, in which there were infinite periods along $x$ axis\textsuperscript{[20-21]}. Here only 4 periods were set as an example (as shown in Fig 5). The asymmetric lamellae-ridges structure had an $x$-invariant period 800nm. The distance between two lamellae-ridges structure was 30nm. In each ridge, the width of trunk was 50nm. The widths of the isosceles trapezoid branches were different and increase equidifferently from 220nm to 400nm along the $z$ axis. The distance between lamellae was 110nm.

![Figure 5. The original model](image)

**Figure 5.** The original model

The two-dimensional model was constructed by DiffractMOD, a general design tool based on the RCWA for diffractive optical structures. For the electromagnetic diffraction by grating structures, the
RCWA was a relatively straightforward technique to obtain the exact solution of Maxwell’s equations. It can be used accurately to analyze the diffraction of electromagnetic waves by periodic structures and even arbitrarily profiled dielectric-metallic surface-relief gratings. The technique was non-iterative and fundamentally stable, thus numerically stable and convergent results can be achieved [22-23].

4. The Simulation Analysis

We attempted to find the influence of structural parameters on the optical characteristics. The spectral reflectivity varied with the change of nanostructural parameters. It was very significant to find out the principles. Specific color can be achieved by designing specific structure. The reflectivity can be set as increase or decrease to meet actual demand.

The model shown in Fig.5 is employed to calculate the spectral reflectivity for both polarizations, monochromatic radiation of wavelengths ranging from 0.3 to 0.8μm at a regular interval of 5nm. Normal incidence was assumed.

4.1. The spectral reflectivity of original model

As shown in Fig.6, the spectral reflectivity of original model almost coincided with the test spectrum of *Morpho Rhetenor* scales at the wave crest in 420-570nm range. But the simulation spectrum was more fluctuant than test spectrum in 350-420nm and 570-780nm. Possible reasons were as follows: firstly, the shape of real nanostructure in scales is irregular curve. It was simplified as regular shape, such as isosceles trapezoid and rectangle; secondly, the real nanostructure has randomness in each size, which was simplified as a fixed value in model.

4.2. Influence of distance between two ridges

The original distance between two ridges ($D$) was 30nm. The reflectivity peak varied obviously with the distance, as shown in Fig.7.

The peak value declined obviously while bandwidth decreased slightly and peak position had tiny move along with the increase of $D$. In particular, the reflectivity decreased in visible range from 380 to 780nm, which indicated a decrease in whole brightness. It was clear that the peak reached 85% of 0-distance, and then dropped to 83% of 30nm-distance, and then 78% of 300nm-distance, and 50% of 1200nm-distance. The variations were non-linear.

The influence of ridge distance was significant to reflectivity in all visible range. Reflective
efficiency can be raised by reducing distance between two ridges, and the color generated from nanostructure would remain as before.

4.3. Influence of lamellae number
The original lamellae number ($N$) was 11. The height of ridge increased with $N$. As shown in Fig.8, the peak value decreased sharply and the peak position shifted to longer wavelengths slightly along with the decrease of $N$. The peak reached 85% of 13 layers in 450 ~ 460nm range. It was dropped to 60% of 6 layers in 460 ~ 470nm range. And the decrease occurred only in the range of wave crest from 430 to 460nm.

The influence of lamellae number was significant to reflectivity just in the range of main wave crest. We can improve reflective efficiency by increasing lamellae number, and the color generated from nanostructure would remain as before.

4.4. Influence of lamellae height
Lamella was simplified as isosceles trapezoid in model. So the height of lamella can be represented by edge length of top ($H$) and the ratio of bottom/top($R$). The $R$ was 1.2 and $H$ was 85nm in original model.

Lamella was rectangle when $R$ is1.

As Shown in Fig.9, reduction of $R$ led to a small decline in peak and a decrease in gradient of wave crest. The peak position moved toward the shorter wavelength. The peak reached 90% as $R=2$. And it was declined to 82% as $R=1$. The difficulty of manufacture increased with $R$.

It can be found from Fig.10, the peak position of spectral reflectivity moved to longer wavelength and the bandwidth increased significantly with the increase of $H$. But the peak value varied merely in a narrow range of 10%. As $H$ was more than 120nm, there was no longer single peak in visible range of 380-780nm. When $H$ was more than 200nm, the anterior peak reached 80% in 390-400nm of blue light range, and the posterior peak was 85% in 740-750nm of red light range. That led to the nanostructure presented a mixed color of blue and red.

The influence of $H$ was significant to color that generated from nanostructure.
4.5. Influence of distance between two lamellae

Distance between two lamellae ($H_0$) was 110nm in original model. The increment of $H_0$ heightened the ridge.

As shown in Fig.11, the peak position shifted to longer wavelength and the peak value increased obviously while the bandwidth increased sharply along with the increase of $H_0$. When $H_0=80$nm, the peak value was just 74% in 410 ~ 420nm of purple light range, and the bandwidth was 90nm from 380nm to 470nm. When $H_0=200$nm, the peak value reached 95% in 570 ~ 580nm of yellow light range, and the reflectivity were more than 70% from 550nm to 760nm.

The influence of $H_0$ was significant to color that generated from nanostructure.

4.6. Influence of the width of lamella

In real scales, lamellae are not equal in width. The top layers are shorter than bottom layers, as shown in Fig.4c. That were simplify as decreasing with layer in model. And lamella was simplified as isosceles trapezoid. So the width of lamella was represented by height of isosceles trapezoid at bottom, which was the maximum width of lamella, and the height ratio of top-layer/bottom-layer. The
maximum width of lamella ($L_{\text{max}}$) was 400nm and the height ratio of top-layer/bottom-layer ($R_L$) was 0.55 in original model.

It can be found in Fig.12, peak value declined obviously while peak position moved to longer wavelength and the gradient declined sharply along with increase of $L_{\text{max}}$. When $L_{\text{max}}$=300nm, peak value was nearly 95%. While $L_{\text{max}}$ was 1000nm, peak value dropped to 65%.

The influence of $L_{\text{max}}$ was significant to reflectivity just in the range of main wave crest. But if we enhanced reflective efficiency by increasing $L_{\text{max}}$, the color generated from nanostructure would be changed as well.

As shown in Fig.13, the gradient declined sharply along with the increase of $R_L$. Wave crest was nearly flat-roofed as $R_L=1$, that means width of every lamella was identical.

4.7. Influence of ridge angle.

Ridge angle ($A_R$) was angle between ridge and base. $A_R$ was 1.5 degree in original model. Ridge height declined along with increase of $A_R$.

It can be found in Fig.14, the peak value increased from 80% to 92% as $A_R$ varied from 0 to 15, and the gradient increased. While $A_R$ more than 15, the peak declined with the increment.

5. Conclusion

The experiments and simulations were accomplished to investigate the reflection properties of Morpho butterfly wing scales. Some principles on the specific structure color can be depicted.

1) The blue color is produced by interference in ridge-lamellae structure, which is composed of alternating layers of high and low refractive index.

2) A narrow gap between the ridges and multi-layers lamellae generates high reflectivity. If the gap is much wider than 1000nm or the lamellae less than 4 layers, the incident light would penetrate the bottom of the multilayer and almost absorb or transmit through the substrate.

3) The ridge-lamellae structure can generate different colors by changing the height of lamellae and the height between lamellae. These two parameters must be less than 200 nm. Otherwise a mixed color is presented.

4) To obtain homochromous on condition of no color change, these parameters, the titling angle of
ridge, height ratio of one lamella and width ratio of lamellae, are significant.

The investigation gives us an opportunity to acknowledge the relation between structural parameters and the reflective color of the *Morpho* wing scales. It enables us to control color and reflectivity by manufacturing nanostructure with specific structural parameter. That should yield a wide variety of applications.

**ACKNOWLEDGMENTS**

This project was funded by National Key Basic Research Special Fund of China (Grant No. 2009CB724204) and National Natural Science Foundation of China (Grant No. 50775091).

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