Investigation on structural colours in wing scales of butterfly *Papilio peranthus Fabricius*

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The microstructure and geometrical dimensions of the scales on a butterfly *Papilio peranthus Fabricius* wing are obtained using scanning electron microscopy and transmission electron microscopy. Two kinds of scales are found in a butterfly wing and the structural colour mainly comes from the cover scale. Different structural models of cover scale that are related to ridge and concavity are constructed and their corresponding optical properties are investigated using the finite-difference time-domain method. It is concluded that the structural colour on the cover scale mainly comes from the sculpted multilayer structure and the ridge on the scale has few effects on the structural colour. When the curvature of the sculpted multilayer structure decreases, the dominant wavelength of colour will shift to a longer wavelength and move slower and slower. The two-dimensional planar multilayer model can be used to calculate the structural colour when the curvature exceeds a certain value.

1. Introduction: Many butterflies exhibit vivid, colourful patterns that are originated from complex interaction between light and sophisticated microstructures on the scales of the wing [1]. These peculiar optical phenomena have attracted great attention in many fields especially in recent rapidly growing fields of photonics [2, 3]. Studying the relationship between the structural colour and microstructure can not only lead to better understanding the mechanism of colour on butterflies, but also helps us to fabricate structural colour through bionic technology [4–6].

Investigations have been carried out for many years and many kinds of scales that can produce structural colour are found in butterflies [7]. One typical scale, referred to as the *Urania* type, comprises a continuous sculpted multilayer structure in the body of scales [8]. The mechanism of structural colour on this type of scale is often explained by the thin-film interference model [9]. Moreover, the optical properties are often calculated by planar multilayer film and effective medium theory [10–12]. Obviously, the effect of ridge on scale has been neglected and the concavity on scale has not been taken into account. As some literatures mentioned [10, 13], when the concavity is deep enough, the polarisation effects on concavities can be observed under a microscope. This means the structural colour will be affected by the concavity on the wing.

The finite-difference time-domain (FDTD) method is quite powerful for studying the interaction of light with the complex structures if the structure and its dielectric permittivity can be described. In recent years, it has been used to analyse the structural colour of *Morpho*-type scale [14, 15]. To our knowledge, there are very few papers that have used FDTD method to analyse the structural colour of *Urania*-type scale, which is more complex than *Morph*-type scale. In this Letter, the microstructure and geometrical dimensions of the scales on a butterfly *Papilio peranthus Fabricius* wing are obtained. Different structural models that are related to ridge and concavity are constructed and their corresponding optical properties are investigated using the FDTD method. Their structural colours are also displayed in a chromaticity diagram.

2. Experiment section: The butterfly in this Letter is provided by the insect museum of Shanghai, China. The bright and vivid part of the wing is chosen as the experiment sample, which is guided by a blue circle (see Fig. 1*a*). The sample was carefully examined using an optical microscope to ensure that there were no structure damages (see Fig. 1*b*).

2.1. Experimental method: Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) are used to character the scale surfaces, cross-sections and concavity profiles. For SEM imaging, the sample is first sputtered with 20 nm thickness of gold and then is observed by an FEI Model Sirion200 electron microscope. To obtain TEM images, the procedure is taken as follows [16]. The sample is placed at 4°C for 5 h after fixing of samples in 2.5% glutaraldehyde. It is then fixed in 1% osmic acid in buffer for 1 h followed by block staining in 70% uranyl acetate for 5 h, dehydration through an acetone series ending with 100% ethanol, and immerging in the solution of epoxy dimethylmethane and Epon with a proportion of 1:0, 1:1, 1:2, 0:1 for 0.5, 2, 1, 2 h, embedding in Epon812. Then, it is put in an oven to harden. Finally, it is sliced into lamellas of 70 nm thickness. The post-microtomed sample is stained with lead citrate and examined with a JEM-1230 TEM.

The reflective spectra of wing scales are measured by a Raman spectroscope (Model: LABRAM-HR) in which the light source is replaced by a halogen lamp lighting system.

2.2. Structural characterisation: From Figs. 2*a* and *b*, it is seen there are two types of scales on the wing, which are named as cover and ground scales individually. Paralleled ridges can be seen on the two types of scales and each ridge runs the full length on each scale surface in one direction. Tiny holes can be found between ridges in the ground scale, whereas many concavities can be seen on the cover scale surface.

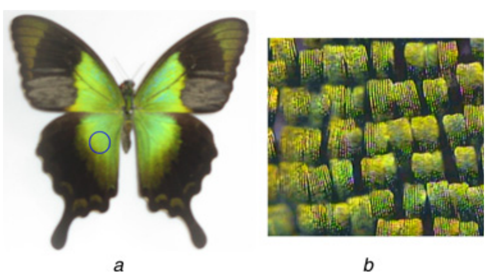

Figure 1 *P. peranthus Fabricius*
a Photograph taken by camera
b Scales on the wing taken by optical microscope

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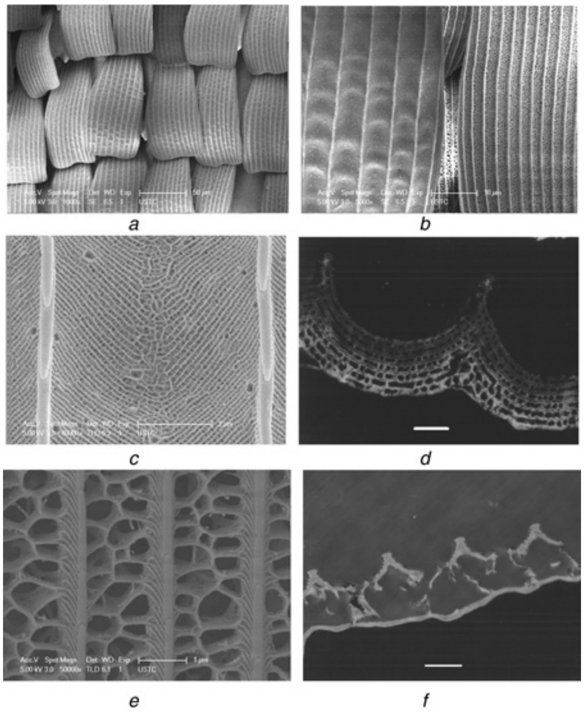

Figure 2 *Micrographs of P. peranthus Fabricius*
a Scales on the wing taken by SEM
b Two type of scales on the wing
c SEM image of cover scale
d Cross-section of cover scale taken by TEM (scale bar: 1 μm)
e SEM image of ground scale
f Cross-section of ground scale taken by TEM (scale bar: 1 μm)

From Figs. 2*c* and *d*, it is seen that each ridge has one to three layer branches on the surface of the cover scale. The distance between the adjacent ridges is about 4–7 μm. Many tiny bars can be found between the ridges on the surface, and the tiny bars near the two sides of the ridges are parallel to each other. The cover scales between the two ridges have many concavities. Parallel to the ridge, the transition between concavities is less abrupt. The longitudinal cross-section shows the scale consists of about 19 alternative chitin and air-chitin layers. This sculpted multilayer structure is commonly seen in *Urania*-type scale. The curvature of the sculpted multilayer structure seems to vary depending on the different location in the scale. The cross-sections of concavities, perpendicular to the ridge, show that the dimensions of each layer in the sculpted multilayer structure remain approximately constant, regardless of position around the concavity. The average thickness of the chitin layer and air-chitin layer is about 0.09 and 0.1 μm, respectively. The fill factors of the air-chitin layer are about 0.67 [9].

From Figs. 2*e* and *f*, it is seen that the distance between the adjacent ridges is about 2–4 μm on the ground scales, which is smaller than that of the cover scale. Many ribs that connect ridges indirectly result in some hexagon-like holes.

3. Analysis and discussion: The scattering of light caused by the ridge or concavity structure described above are studied by the software provided by FDTD Solutions Inc. The model structures are illuminated by a normally incident plane wave. The computations for transverse electric (TE) polarised fields and the transverse magnetic (TM) polarised field are performed separately. The optical spectra are the average of TE and TM waves. The chitin of the scale has a complex refractive index of about 1.56 + 0.06i [17, 18].

As for the ground scale, the structural model is established as shown in Fig. 3*a* and reflectivity is <0.1 through simulation as shown in Fig. 3*b*. It is concluded that this type of scale cannot produce the structural colour. This result is also verified by the experiment [19]. So it can be concluded that the structural colours on this butterfly's wings mainly originate from the cover scales.

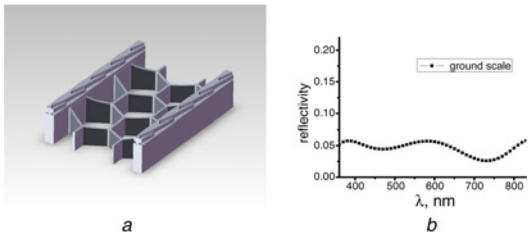

Figure 3 *Optical propertities of ground scale*
a Structural model of ground scale
b Reflectivity of model simulated by FDTD method

3.1. Effect of ridge on cover scale: With the fine texture on the surface and the transition between concavities parallel to the ridge neglected, two structural models are set up corresponding to the cover scale mentioned above as shown in Figs. 4*a* and *b*. The difference between the three-dimensional (3D) model and 2D curved multilayer model is that the first has a ridge structure, whereas the latter only has a multilayer structure. The curvature of the concavity profile can be expressed by the radius, *R*, which is shown in Fig. 4*c*. The value of *R* is 9 μm and the reflective spectra of the two models simulated by the FDTD method are shown in Fig. 5*a*. It can be seen that the reflective spectrum of the 2D curved multilayer model is in close agreement with that of the 3D model.

To present the colour appearance of the scale, the CIE 1931 colour space chromaticity is used to express the chromaticity [20]. The wing scale is illuminated by the normalised illuminant D65, which closely matches daylight. The chromaticity coordinates for the two models are (0.274, 0.481) and (0.270, 0.481). The colours are, respectively, shown in Fig. 5*b*, which is guided by different colour circles. It can be seen that the colours of the two models are almost the same. That is to say, the ridges on the scale surface have little effect in structural colour. So the reflective spectrum of the whole scale can be obtained from the 2D curved multilayer model.

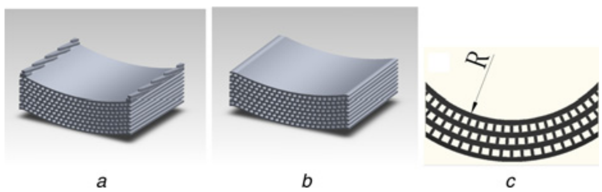

Figure 4 *Structure models of cover scale*
a 3D model
b 2D curved multilayer model
c Curvature of concavity profile represented by parameter *R*

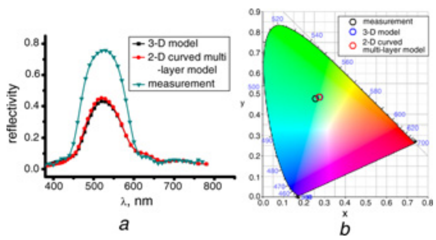

Figure 5 *Effect of ridge on cover scale*
a Reflectivity of two simulated models and experiment measurement
b 1931 International Commission on Illumination (CIE) chromaticity diagram with the colour coordinates in *a*

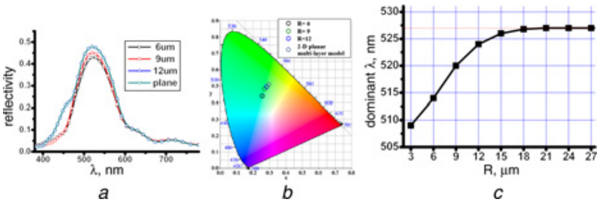

Figure 6 *Effect of concavity on cover scale*
a Reflective spectra of 2D curved multilayer model which have different curvature
b 1931 International Commission on Illumination (CIE) chromaticity diagram with the colour coordinates in *a*
c Dominant wavelength of colour increasing slower and slower when the curvature *R* increases

3.2. Effect of concavity on cover scale: The concavity profiles will affect the structural colour and the curvature of the sculpted multilayer structure should be taken into account. Optical microscopy images show colour variations from the concavity centres to their edges and polarisation effects will appear when the concavity is deep enough. In some applications such as the anti-counterfeiting field, polarisation effects will be fabricated by mimicking this type scale structure [2]. In this case, macroscopic appearance that is related to concavity should also be discussed.

Fig. 6*a* shows reflective spectra of different curvatures of 2D curved multilayer models and their corresponding colours are shown in Fig. 5*b*. It can be seen that when radius *R* is increased, the dominant wavelength of colour will shift to a longer wavelength and the shift will move slower and slower. When *R* exceeds 18 μm, the dominant wavelength will almost no longer shift and the colour has hardly any change. It is concluded that when the concavities are not deep and the curvature of the sculpted multilayer structure reduce to 18 μm, the 2D curved multilayer model can be represented by the 2D planar multilayer model to calculate the reflective spectrum and structural colour.

4. Conclusion: The microstructure and geometrical dimensions of the scales on a butterfly *P. peranthus Fabricius* wings are obtained. Two kinds of scales are found in wings and the structural colour of the butterfly mainly originates from the cover scale. It is concluded that the structural colour of the cover scale mainly comes from the sculpted multilayer structure and the ridge on the scale has little effect on the structural colour. The curvature of the sculpted multilayer structure will affect the structural colour. The dominant wavelength of colour will shift to a longer wavelength and the shift will move slower and slower when the curvature increases. When the concavities are not deep and their sides are not steep to the plane of the scale, the 2D planar multilayer model can be used to calculate the structural colour.

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