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Excellent Color Sensitivity of Butterfly Wing Scales to Liquid Mediums

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Abstract

The ultrastructure characteristic and vivid colors of butterfly wing scales have attracted considerable attention recently. Surprisingly, these hyperfine structures also endow butterfly *Trogonoptera brookiana* wing scales the excellent color sensitive property to liquid mediums. In this work, the characteristic features of this excellent functional surface and the mechanism of its highly sensitive response characteristics were investigated. Firstly, the extraordinary and ordered nanostructures of this butterfly wing scales were characterized by a Field Emission Scanning Electron Microscope (FESEM). Then, the ultra-depth three-dimensional (3D) microscope was used to observe the sensitive discoloration effect of the scales to liquid mediums. Afterwards, the highly spectral sensitive feature was identified by a mini spectrometer. In addition, the mechanism of this color sensitive effect of butterfly wing scales was revealed through modelling, calculation and simulation. It was found that this sensitivity is caused by the combined action of the microscale scales and the ultra-fine nanoscale structures in scale surface. On one hand, the arched and bended cover scales were stretched and superimposed by the filled ether solution. So, the color of the scales became reddish brown in an instant. On the other hand, the change of the fill mediums with different reflective index induced the modification of the surface interference, resulting in the peak shift of the reflectance spectrum. More importantly, the results of simulation and theoretical calculation were both in agreement with the experimental results. It illustrated that the butterfly *Trogonoptera brookiana* wings have repeatable sensitivity to liquid mediums, and obvious discoloration sensitive effect. This spectral sensitivity of butterfly wing scales has great prospect and meaning for the basic research and application of cheap, environmentally free and biodegradable sensitive element for water quality monitoring and analysis system.

Keywords: color sensitivity, micro and nanostructures, butterfly wing scales, bionics

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1 Introduction

Iridescent colors of beetles and butterflies always draw great attention[1]. Researchers have made great efforts for the color formation mechanism. As studies continue, researchers find that most colors are caused by the particular structures that can be observed from the wing surface of insects, such as beetle *Chrysochroa fulgidissima*[2,3], beetle *Eupholus magnificus*[4], beetles *Cyphochilus* and *Lepidiota stigma*[5], butterflies *Papilio*[6], butterfly *Callophrys rubi*[7], butterfly *Polyommatus icarus*[8], butterfly *Papilio peranthus*[9] and some other insects[10,11], spiders, birds, fishes and other marine animals. This iridescent color is called structural color. In fact, the structural color is produced by physical interactions of light and the nanostructures which have the same order of magnitude with the wavelength of the visible light[7]. So, the structures of insects are also seen as photonic structures. Photonic structures have been developed in nature for millions of years before our initial attempts[12]. Diversification of photonic structures, most of which are complex and hierarchical, has widely presented on the surfaces of a variety of animals such as butterflies[13], beetles and marine animals in recent surveys[14–17]. Remarkably, the photonic structures of butterfly scales are also know as Photonic Band Gap (PBG) materials[18]. The potential applications of PBG have made considerable progress and development, such as selective gas sensors[19,20], infrared detection[21], cosmetics, functional coatings[22],

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display technology[23,24] and structural-color devices[25]. So, more and more scholars began to study the photonic structures, especially the hierarchical structures of butterfly wings scales[26,27].

The multi-functional characteristics of butterfly wing scales, including hydrophobic, lightweight, visual effects, mechanically strong and thermal regulations are revealed as a result of photonic nanostructures in the ridges of some butterfly scales[28,29]. Colors of the wings could change with the viewing angle. Such optical properties depend strongly on the wavelength, angle of incident light and the observation[30]. Some butterflies are famous for their structural color[31,32]. Butterflies *Eryphanis reevesi*, *Morpho aega* and *Morpho menelaus* exhibit strong iridescent blue color, which is attributed to the discrete "Christmas-tree" structures in their wing scales[33]. Butterflies *Papilio ulysses* and *Papilio blumei* exhibit gorgeous colors, which are also attributed to the multilayer concavities[1]. Notably, butterfly *Morpho Menelaus* gives a different optical response to surrounding medium[34]. It is the rules or irregular arrangement structures resulting in its strong sensitivity. Surface of butterfly wings is not easy to attach the water droplets, exhibiting excellent hydrophobicity. However, the organic solvent is easily attached to its surface. Most recent studies have shown that the properties of some butterfly scales can be utilized for temperature perceptions and gas detections[19,35]. Although great achievements has been made, mechanism of structure-based color sensitive effect of butterfly wing to toxic gas still faces doubts and remains to be a big challenge. Photonic structure of butterfly wing scale is a good sensor prototype. Thus, investigating the relationship between the structures and the sensitivity features is of vital importance.

In this work, the biophotonic nanostructures and ether-sensitivity mechanism of butterfly *Trogonoptera brookiana* scales were investigated. Firstly, the extraordinary and ordered nanostructures of the wing scales were characterized by FESEM. The ultra-depth three-dimensional microscope was also used to observe the color change images of scales to ether solution. Then, the highly spectral response feature was identified by a mini spectrometer (Ocean Optics USB4000). Afterwards, the mechanism of the color sensitivity effect to ether solution was illustrated by the theory of multilayer-thin-film interference. Finally, the test results were simulated by the software *Translight*. Importantly, the comprehensive and deep understanding sensitivity characteristics of this butterfly will not only help us to study architectural features, but also help us to mimic the photometric characteristics for the research and application of sensitive elements.

2 Materials and methods

2.1 Biological samples of butterfly wings

In this work, the scales on butterfly *Trogonoptera brookiana* wings were taken as the experimental samples. As shown in Fig. 1, there are some green regions symmetrically distributed in the front and hind wings. The triangular green zones were chosen as the experimental areas to be studied carefully.

2.2 Discoloration experiments

In the whole process, all operations were implemented on original butterfly wings[36]. First, a drop of ethanol was applied onto the experimental areas under stereomicroscope. Then, the time-elapsed change of scale color was tracked and recorded with ten-second interval for 1 min. It has been shown that ethanol is a

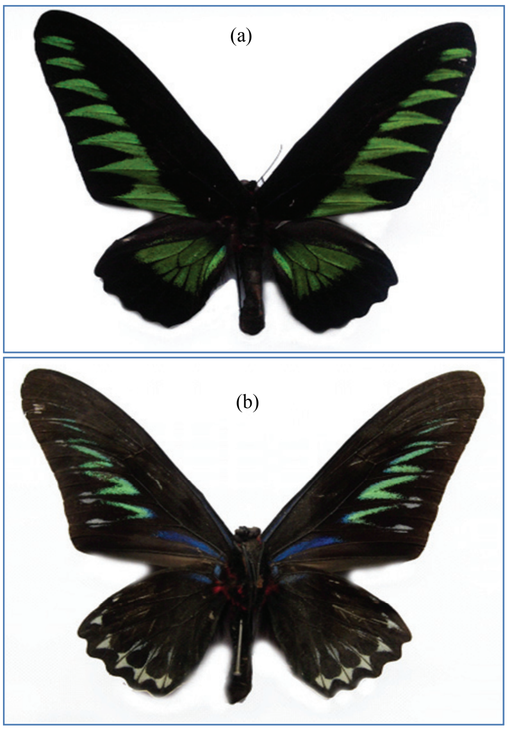

Fig. 1 Macroscopic morphology of the original butterfly *Trogonoptera brookiana* wings. (a) Some green area in front wings. This green region is triangle; (b) some blue scales in hind wings. The ventral surface is brown in appearance. Other parts of the body are all black scales.