Imaging System Free of Dyes and Pigments
- Study of the Structural Color of Organisms -

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Abstract

Structural color is of significant research interest as it may yield novel coloring systems that use neither dyes nor pigments. The origin of their coloring principle is their extremely minute physical structures, the sizes of which are comparable to the wavelengths of light. Structural color is observed in many organisms such as insects, shells, and birds, and models of their coloring mechanisms have been proposed. This study aims to confirm the mechanisms of the structural color of different organisms. Coloring mechanisms of a Jewel beetle, a Morpho butterfly, a Turban shell, and a Peacock, for which models have been suggested, are verified by observing their colors when (1) the colored surfaces are immersed in two liquids with of different refractive indices, and (2) through a polarizing filter. The results invalidate one of the conventional explanations for the jewel beetle: a grating structure on a Jewel beetle was not agreed by our experimental results. For the Morpho butterfly, the results suggest a better explanation, a grating structure, than the conventional one: multilayer reflection. This decision is supported by the results of a spectrum analysis. Our approach to the examination of structural color mechanisms can be expected to suggest new imaging systems that are completely different from the systems in current use.

1. Introduction

Taking our cue from the world of nature, color systems based on minute physical structures should be possible. The key is structure size; it should be roughly equivalent to the wavelengths of visible light to create light interference effects. Such systems have exciting since they use neither dyes nor pigments.

Let's compare the coloring principle of the structural color with that of conventional dyes and pigments. The coloring principle of pigments has two parts: light absorption (transformation from light energy into electron energy) and radiation (transformation from electron energy into light energy). On the other hand, the coloring principle of the structural color arises from the light interference effects, including diffraction and scattering, created by minute physical structures on the light path.

The goal of this study is to realize a novel imaging system based on structural color. The first step of this study is to investigate the structural colors of such as insects, birds, and shells. The microscopic structures of the surfaces of these organisms have already been investigated using electron microscopy: their extremely fine structures have suggested different structural coloring mechanisms, but no detailed analyses or groupings of such mechanisms have been published.

This study aims to verify and group the mechanisms of structural color exhibited by various organisms. Coloring mechanisms of a Jewel beetle, a Morpho butterfly, a Turban shell, and a Peacock, for which models have already been published, were verified, as a first step. Our verification process included observing the colors seen when the colored surfaces were immersed in liquids of different refractive indices (Experiment 1), and when observed under a polarizing filter (Experiment 2). The Morpho butterfly, whose color changed strongly with the liquid's refractive index, was subject to a further investigation. In Experiment 3, we measured the reflection spectrum of Morpho butterfly scales to elucidate which kind of interference mechanism dominated the coloring systems.

2. Verifying Structural Coloring Mechanisms of Various Organisms (Experiments 1, 2)

2.1 Experimental Methods

In Experiment 1, colored surfaces of a Jewel beetle, a Morpho butterfly, a Turban shell, and a Peacock feather were observed when immersed in two liquids of different refractive indices (Fig.1): ethanol (n=1.36) and toluene (n=1.49).[5] In Experiment 2, the surfaces were observed when placed under a polarizing filter. The observed colors and changes in color were used to assess the validity of the traditional explanations of coloring mechanisms of each organism.

2.2 Results of Experiments 1 and 2

The results of Experiment 1 are shown in Table 1. No change in color was observed for the Jewel beetle, the Peacock, and the Turban shell. The Morpho butterfly was the only organism whose color changed. The observed change is shown in Fig.2. In Experiment 2, the Jewel beetle yielded the only change: a slight change from green to blue.

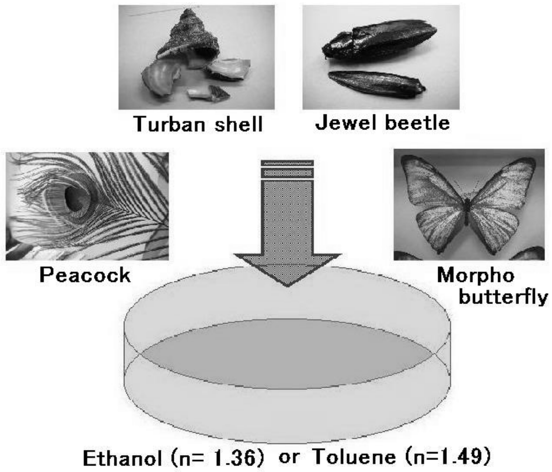

Figure 1. Observation of surfaces in ethanol or toluene

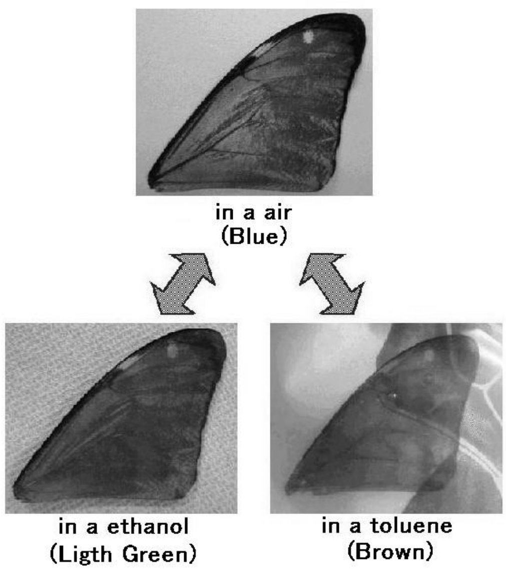

Figure 2. Appearance change of a Morpho butterfly absorbed in ethanol or toluene

Table 1. Appearance of four surfaces immersed in ethanol and toluene

Sample of observation	Coloring change by liquids		
	Air (n=1.0)	Ethanol (n=1.3)	Toluene (n=1.5)
Jewel beetle	Green	Green (Slightly bluish)	Green (Slightly darkish)
Turban shell	Opal	Opal	Opal
Peacock	Yellow Green Blue	Yellow Green Blue	Yellow Green Blue
Morpho butterfly	Blue	Light Green	Brown (Transparent)

2.3 Discussion of Experiments 1 and 2

Table 2 summarizes results of Experiments 1 & 2 and compares the results gained to those predicted by conventional coloring mechanisms for each organism; two mechanisms have been suggested for the Jewel beetle. More detailed comparisons are given below.

1) Jewel Beetle: The first conventional explanation, the color mechanism is a diffraction grating, is contradicted because there was virtually no color change in the immersion test.

   On the other hand, the second explanation, the surface consists of cholesteric liquid crystal material, was supported by the color change seen under the polarizer.
2) Turban shell: The conventional explanation of interference created by thin film layers was not contraindicated by either test.
3) Peacock: The conventional mechanism, interference by Mie scattering, is contraindicated by the immersion test but not the polarizing test: no color change was observed. The conventional explanation cannot be categorically denied because it is rather doubtful that the liquids permeated the structure fully in our test.
4) Morpho butterfly: The conventional explanation, interference by reflections among multiple layers, is supported by the immersion test, and not denied by the polarizing test. It should be noted that another explanation, its surface structure acts as a diffraction grating[7] is also supported by the results of these two experiments.

We grouped, based on these results, the coloring mechanisms, and tested surfaces into three groups: thin film type, minute structure type, and cholesteric liquid crystal type.

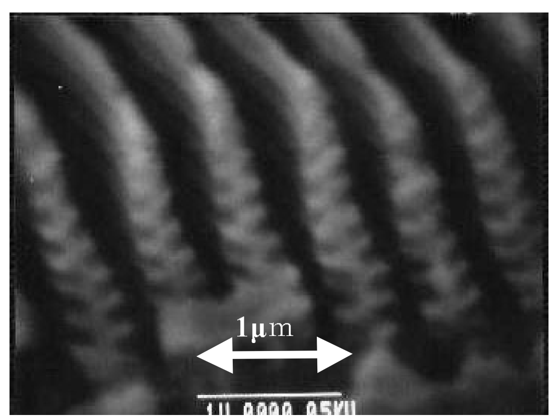

Figure 3. Cross section of scales of a Morpho butterfly（SEM observation）

Table 2. Color change of four organisms

Observed organisms	The traditional theory	Experiment 1			Experiment 2		Summarized conclusion on mechanisms
		Color change in the test liquids		Agreement or disagreement to conventional explanations	Changes by polarizing plate	Agreement or disagreement to conventional explanations	
		ethanol	toluene				
Jewel beetle	Cholesteric liquid crystal[2]	almost none	almost none	Agree	Change	Agree	Cholesteric liquid crystal type.
	Grating[1]			Disagree		Disagree	
Turban shell	Interference on thin film layer	None	None	Agree	None	Agree	Thin film type
Peacock	Interference by Mie scattering,[4]	None	None	Disagree	None	Agree	Minute structure type.
Morpho butterfly	Interference by reflection among multiple layers[3]	Change	Change	Agree	None	Agree	

3. Further Study on Morpho Butterfly

3.1 Purpose of Further Study

We compare two color mechanisms for the Morpho butterfly: the conventional mechanism of interference by reflection among multiple layers, and the new explanation of a diffraction grating within the surface structure.

The conventional explanation is that the structural color of the Morpho butterfly is caused by the interference established by a multilayer film. However, the observed image by SEM (Fig.3) could allow us to find not only multilayer structure, as seen as multi-shelves, but also a grooved grating structure on it. The dependence of the surface's reflection characteristics on lighting directions was measured; only if the surface has the characteristics of a grating structure should it show a drastic dependence on direction.

3.2 Experimental Method (Experiment 3)

The reflectance and spectrum of light reflected from a scale of a Morpho butterfly was measured on two axes: parallel and perpendicular to the micro grooves on the scale. The directions tested are shown in Fig. 4 as (c→d, d→c, a→b, b→a).

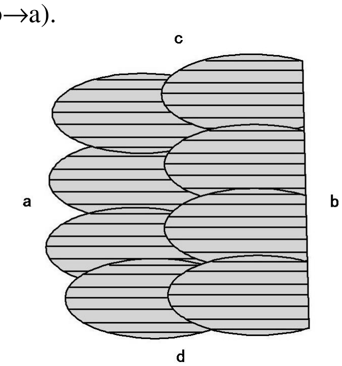

Figure 4. Four measurement directions on the scales of a Morpho butterfly: c→d, d→c, a→b, b→a.

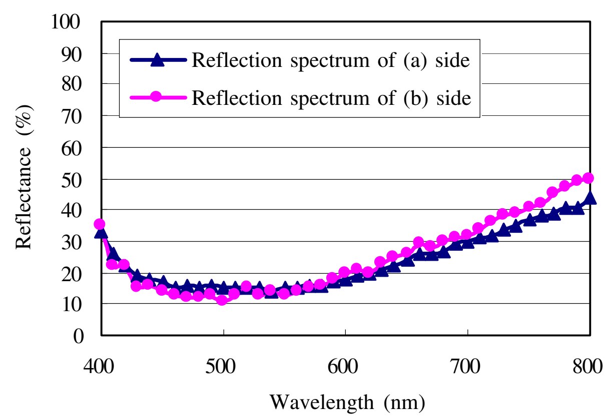

Figure 5. Reflection spectrum on direction parallel to grooves on scales of a Morpho butterfly

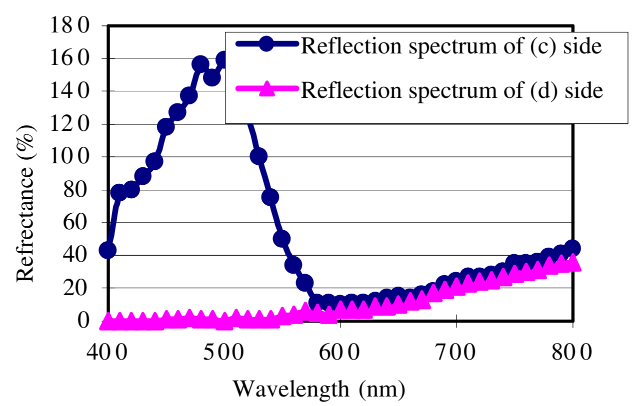

Figure 6. Reflection spectrum on direction perpendicular to grooves on scales of a Morpho butterfly

3.3 Experimental Results

The measured spectra are shown in Fig. 5 (perpendicular) and Fig. 6 (parallel). The reflection spectrum captured on direction (c) shows a remarkable peak at around 500 nm: the color observed was brilliant blue. The reflection spectrum on the opposite direction shows, on the other hand, no peaks anywhere and very small reflectance at short-wavelength: the color observed was brown. The reflectance on both parallel directions was rather flat; the color observed was brown.

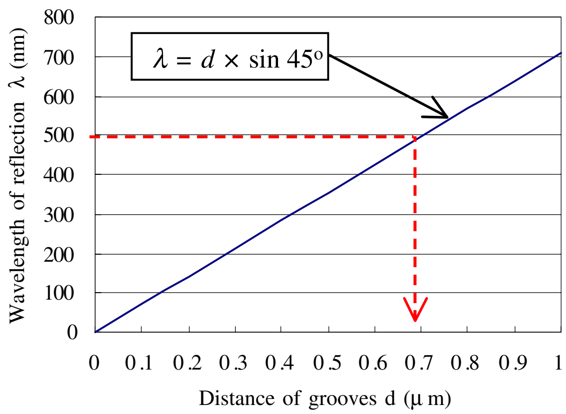

Figure 7. A relation between grooves of grating and wavelength of reflection light

3.4 Discussion of Experiment 3

The spectrum characteristics support the existence of a grating structure. We note that the reflection spectrum corresponding to blue color appearance was observed only perpendicular to the grooves.

The pitch needed to realize blue reflection is calculated theoretically for a grating as follows.

$$d(\sin\alpha + \sin\beta) = m\lambda \ (m = 0, \pm 1, \pm 2\ldots)$$

d: groove spacing, α: angle of incidence
β: angle of diffraction, m: grating constant
λ: wavelength

The angle of incidence α is 0° and the angle of diffraction β is 45° at the condition used in Experiment 3. The number m is 1 when we deal with primary diffraction light. The wavelength λ of diffraction (reflection) light is given by:

$$\lambda = d \times \sin 45°$$

The calculated relation between λ and d is shown in Fig. 7, groove spacing (d) in the range of 0.1 μm to 1.0 μm. When we assume λ = 500 nm, which is the observed peak wavelength for the Morpho butterfly, the calculated groove spacing of the grating d equals 0.7 μm. This calculated groove spacing agrees with the spacing (0.5 - 0.8 μm) observed in the SEM image shown in Fig. 3.

An unsolved question is why the scales exhibited color diffraction from just one direction: a clear blue. Explanations include unexpected sample inclination or some more complicated anisotropic structure than a simple grating. These assumptions should be verified in the next stage of this study.

4. Summary

The structural color mechanisms of organisms were studied for the purpose of developing a novel color imaging system. Main results are summarized as follows.

1) The conventional explanations of structural coloring mechanisms were verified for various organisms by observing their colors when immersed in liquids of different refractive indices (Experiment 1), and when placed under a polarizing filter (Experiment 2). One key result is that the grating structure advanced for the jewel beetle did not match by our experimental results.
2) For the Morpho butterfly, we advanced the new explanation of a grating structure as a rival to the conventional mechanism of multilayer reflection. This explanation is supported by all the results of our experiments including the experiment that conducted a spectrum analysis (Experiment 3). The conventional explanation is not supported by this third experiment.

Reference

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Biography

Yoichi Nomura was born in 1979. He received his B.S. degree in 2002 from Tokai University. He is expected to receive his M.S. degree from Graduate School of Tokai University in 2004. He is now studying the structural color.