Study on the microstructure and its coloration mechanism of peacock feather by the FDTD method

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Abstract. Animal body colors have attracted researcher’s attention because of their functions of reducing accessibility to predators, helping to capture prey, helping to court and so on. In the paper, peacock feather structure and mechanism of forming colors were relatively systematically studied. The experimental data of the microstructure of green male peacock “eyespot” parts were obtained, and their reflective optical characteristics were tested. The theoretical results simulated using a finite difference time domain method are well consistent with the above experimental results. Therefore, it was confirmed that peacock feather structural colors mainly come from two-dimensional photonic crystal structure. It further proves that the feasibility of the finite difference time domain method. This study is of great significance in printing and dyeing industry, textile industry and other fields in China.

Keywords: photonic crystal; peacock feather; structural color; coloration mechanism.

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1. Introduction

It is generally believed that colors of living creatures are mainly pigmentary colors in nature. However, it is found in studies that there also exist structural colors and combination colors, besides pigmentary colors. Compared with pigmentary colors, structural colors have such advantages as being of high saturation, high color brightness, with rainbow effect, being of environmental protection, never fading away and so on [1-3]. Therefore, structural colors of living creatures have long been of interest to researchers, and more and more of them are engaged in researching animal body colors. Studies have found that male peacock feathers are a typical representative of structural colors of living creatures. Li et al [4] studied the characteristics of the structure of peacock feathers after they made a careful observation of the structure...
of peacock feathers, but they did not carry out a systematic research on the precise physical mechanism which produces diverse colors in peacock feathers. Zi et al [5] reported the mechanism of color production in peacock feathers by a plane-wave expansion method. Recently, finite difference time domain (FDTD) method is widely used to simulate the optical properties because of its accuracy and ability to deal with complex structures. However, to date, there have been no reported attempts to study the coloration mechanism of peacock feather by the FDTD method.

In the present paper, after peacock feather structure and its mechanism of forming colors were analyzed, a detailed description of its physical mechanism and regulating-controlling principles were given, which were expected to be applied, with bionic technology, to such industries as printing, textile, cosmetics, and artificial photonic crystal production and so on [6-9].

2. Theoretical Research on the Mechanism of Forming Colors of Peacock Feathers

The basic idea of FDTD [10] is: dividing a primitive cell which comes from real space of an electromagnetic field into a lot of network elements, and then directly associating the magnetic field (electric field) of one grid point with the electric field (magnetic field) of its nearest grid point in the process of calculation, i.e. each component of the magnetic field (electric field) is surrounded by four components of the electric field (magnetic field); in time and space, E and H are interlaced. When the differential equations of the curl equations of Maxwell equations are directly replaced with finite difference formula, if appropriate boundary conditions are used, Maxwell equations can be transformed into equations in a matrix form.

In order to multiply offspring, peacocks have developed bright plumage in the long-term evolution process. The “eyespot” parts in male peacock's feathers are the most delicate parts, which are blue, green, brown and yellow successively from center to outside. An experimental study of the structure of peacock feathers was conducted by Zi et al [5]. After the micro-structure of the barbules were observed with a scanning electron microscope, it was found that there exits two-dimensional photonic crystal structure beneath the barbule’s epidermis which are formed by keratin rods [11-12]. It can be known that there are periodic two-dimensional photonic crystals in male peacock feathers which are composed of such three media as melanin granules, keratin and air, three of which are arranged according to certain rules. (See Table 1).

| Media                  | Melanin Granules | Keratin | Air  |
|------------------------|------------------|---------|------|
| Refractive Index       | 2.0+0.1i         | 1.54    | 1.0  |

If the transverse lattice constant is labeled X, the longitudinal lattice constant is labeled Y, the lattice constant a, the radius of long linear rods R, and the radius of air holes r, then the structural parameters could be summarized as follows (see Table 2) [12].

| Color  | X    | Y    | a    | R    | r    | R/a  | r/a  | Period |
|--------|------|------|------|------|------|------|------|--------|
| Blue   | 126 nm | 126 nm | 126 nm | 50 nm | 21 nm | 0.4  | 0.15 | 9~12   |
| Green  | 145 nm | 145 nm | 145 nm | 60 nm | 22.5 nm | 0.4  | 0.15 | 9~12   |
| Yellow | 156 nm | 156 nm | 156 nm | 66 nm | 24.75 nm | 0.4  | 0.15 | 6      |
| Brown  | 148 nm | 165 nm | 165 nm | 68 nm | 27 nm  | 0.4  | 0.15 | 4      |
In this part, a structure model was built to carry out theoretical simulation by calculation, and, at the same time, another kind of simulation was conducted with a FDTD software. When reflection spectra were fitted out, they were compared with the results obtained in the experiment.

With the help from a variety of observation instruments, it was found that the structure of the barbule’s epidermis of peacock feathers is a rectangular grid which is approximately like a square, that is to say, 2D photonic crystal structure with a square shape. Their refractive index and structure parameters could be gotten in Table 1 and Table 2.

![Figure 1](image1.png)

**Figure 1.** Structural diagrams of the green area in “eyespot” part of male peacock. Feathers from different viewpoints in the case of normal incidence.

According to the basic idea of FDTD and the above-described microstructure of peacock feathers, especially on the basis of the parameters in Table 1 and Table 2 of the microstructure of peacock feathers, the microstructure of peacock feathers, i.e. two-dimensional square photonic crystals, was designed and simulated with a FDTD software. First, the structure of the green area in the “eyespot” part of male peacock feathers was taken as an example (See Figure 1).

Figure 1 shows the diagrams of FDTD structural models of the green area in the “eyespot” part of male peacock feathers from different viewpoints in the case of normal incidence. The diagrams are xy plane view, xz plane view, yz plane view and views of different angles respectively.

![Figure 2](image2.png)

**Figure 2.** Reflection spectra of different colors simulated with TM model.
By the FDTD simulation diagrams of the green area in one "eyespot" of male peacock feathers (see Figure 1), the reflection spectra of the green barbules were obtained (see Figure 2). In Figure 2, it can be seen that the center wavelength corresponding to the major reflection peak of the green barbules is 565 nm that exactly falls in the visible light green band. In the same way, the structural models and their reflection spectra of the blue area, the yellow area and the brown area had been simulated with a FDTD software, as are shown in Figure 2. It can be seen that the center wavelengths corresponding to the major reflection peaks of the blue, yellow and brown barbules are 465 nm, 597 nm and 649 nm that exactly fall in the visible light blue, yellow and brown bands respectively. Therefore, it could be concluded that the rich colors of male peacock feathers come from the two-dimensional photonic crystal structure beneath epidermis.

![Figure 3. Reflection spectra, with different refractive indexes, of the green area in the “eyespot” part of male peacock feathers.](image)

When feathers were soaked in ethanol solution with a concentration of 80% at 35 °C, the refractive index of air holes increased from 1 to 1.38, thereby leading to an overall increased refractive index. Thus, the reflection spectrum of the green barbules by FDTD simulation is shown as Curve 2 in Figure 3. Similarly, when feathers were soaked in ethanol solution with a concentration of 70% at 25 °C, the refractive index of air hole became 2. Then, the peak in the reflection spectrum of the green barbules shifts to longer wavelength, as shown in Figure 3, Curve 3. In Figure 3, it can be seen that the reflection indexes of the major peaks of the reflection spectra, curve 1, 2, 3, gradually decrease and the center wavelengths corresponding to the reflection peaks increase gradually. Curve’s color changes too, and this is a red shift which is due to an increase in feather’s refractive indexes. Ethanol is colorless and, therefore, the change in color is not due to pigmentary color. A similar conclusion has been reached by Zhang et al. in their experiments after observing the reflection spectra of the feathers soaked by isopropyl alcohol [13]. The fact that what Figure 3 shows is in agreement with the results from experimental observation proved, once again, this paper’s hypothesis that the diverse brilliant colors of peacock feathers primarily originate from the structural colors of the two-dimensional photonic crystals beneath the barbule’s epidermis.

3. Conclusion
On the basis of experiments, theoretical calculation and simulation had been carried out and finally the mechanism of forming color was discovered of male peacock feathers. There exists square lattice 2D photonic crystal structure in male peacock feathers. Peacocks can regulate and control the reflection peak’s position which is known as “forbidden band” by changing the cycle length of photonic crystals.
Moreover, it was also found that the reason why white peacock feathers and female peacock feathers are not of gorgeous color is that there exists no two-dimensional photonic crystal structure.

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