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Towards high thermal stability of optical sensing materials with bio-inspired nanostructure

Xiao Yang [a,c,*], Luo Zhang [a], Meng Yang [b], Shichao Niu [c], Honglie Song [c,d], Jing Ni [a], Can Wu [a], Guojin Chen [a]

[a] School of Mechanical Engineering, Hangzhou Dianzi University, Hangzhou 310018, China
[b] Hangzhou Branch of Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Hangzhou 310013, China
[c] Key Laboratory of Bionic Engineering (Ministry of Education), Jilin University, Changchun 130022, China
[d] Applied Mechanics Laboratory, Tsinghua University, Beijing 100084, China

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ABSTRACT

The optical properties of iridescent nanostructures which were found in butterfly scales were investigated under varied temperature. An amazing hierarchical nanostructure with high thermal stability was revealed for the application of bio-inspired optical materials. Relationship between thermal dilation and light reflectance of the typical iridescent nanostructures including the ridge-specialized and body-lamellae structure were carefully studied by experimental tests and computer simulation. Results of experimental tests showed the light reflectance of the body-lamellae nanostructure performed more stable. Finite element methods and FDTD (Finite-Difference Time-Domain) solutions revealed the effect of thermal dilation and structural parameters on light reflectance. The results guided the design of future optical sensing materials with a high thermo-optic stable nanostructure.

1. Introduction

An astonishing variety of natural photonic structures were achieved by natural creatures over 500 million years, such as butterflies use multiple layers of cuticle and air to produce striking colors, brittlestars use photonic elements composed of calcite to collect light, and some insects use arrays of elements to reduce reflectivity [1]. These optical nanostructures provide inspirations for future materials that related with visual sense. Butterfly scale was one of the most magical iridescent structures which caused a lot interesting to study. The optical performance had been well investigated and the mystery behind the iridescent color had been revealed [2,3]. Two typical nanostructures were found, one was the ridge-specialized structure (RSS) the other was the body-lamellae structure (BLS). Models of manipulating light of these two structures were established, including thin-film interference, multilayer interference, and diffraction grating effect [2]. Based on these models, many applications were inspired such as vapour sensors [4], infrared detection [5], solar cell [6].

However, light is always accompanied with heat which reduces the optical sensitivity due to thermal dilation, even little heat for an intricate structure at nano scale size would cause a large thermal dilation. Some scholars studied the effects of heat on the reflecting spectroscopy, including heating and cooling [3,7], and tried to improve optic readout by depositing a Au layer on scales [4]. But, the studies focused on the thermo-optic properties were still very few, and seldom found the theoretical models established precisely to study the relationship between thermal dilation and light reflectance. Thus, studying the thermo-optic performance under varied temperature is significant for developing optical sensing materials with a high thermal stable nanostructure, especially for the infrared detection or the materials used in harsh temperature environment.

2. Materials and methods

The wings of Morpho Menelaus (MM) and Papilio Ulysses (PU) were cut into square piece with the dimensions of 10 mm * 10 mm. The test samples were cleaned and the reflection spectra were measured by Ocean Optics USB400 spectrometer. Its detector range covered from 300 nm to 1100 nm with the resolution of 0.1–10.0 nm. Measurements were carried out immediately without cooling by water after the scales were heated up 2 h in the vac-

* Corresponding authors at: School of Mechanical Engineering, Hangzhou Dianzi University, Hangzhou 310018, China (X. Yang and G.J. Chen).

E-mail addresses: yangxiao0431@foxmail.com (X. Yang), chenguojin@163.com (G. Chen).

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uum drying oven (Shanghai Xunbo BZF-30) of which setting temperature was 50 °C. Reflectivity was measured every 10 s without changing the position and testing angle. The microstructures of the scales were studied by scanning electron microscope, EVO 18 ZEISS. The physical properties of butterfly scales used in simulations were: the refractive index was $n = (1.55 \pm 0.05)$ + i (0.060.01) [8]; the thermo-optic coefficient was $dn/dT = -4.7{*}10^{-4}\,°C^{-1}$ [4]; the thermal expansion coefficient was $\alpha = 50$ ppm/°C [4]; the elastic modulus was $E = 0.51–2.97$ Gpa [9]; specific heat $c = 2.55$ J/(kg·°C) [10].

3. Results and discussions

Two iridescent nanostructures of butterfly scales were revealed, one was the RSS, the other was the BLS as shown in Fig. 1. RSS and BLS were well known structures for their excellent properties of manipulating light [2].The iridescent RSS and BLS presented a striking blue color due to the reflecting peaks located between 450 nm and 550 nm as shown in Fig. 2(a, b). However, the reflecting peaks drifted differently after heating which indicated they have a different thermo-optic performance. Professor László Péter Biró also verified that the shift of reflecting peak was related with the alteration of the dimensions of the photonic nanostructure or the changes in the scale arrangement which induced by temperature variation.

To evaluate the reflection spectra of the thermal responses, the reflectivity of RSS and BLS were transformed according to

$$\Delta R = 100\% * [R_n/R_0]$$

where R_n is the reflectivity, and n = 0, 10, 20, 30, 40 respectively which represent the time after heating. The results were showed in Fig. 2(c, d), it was found the reflecting performance of BLS was more stable after heating. Because the maximum ΔR of RSS was almost 3, and ΔR of BLS was only 2. Moreover, the drifting band of RSS was larger, there were two peaks among 500 nm and 700 nm, but there was only one peak in the reflection spectra of BLS. The ΔR of BLS was smaller which indicated the effect of thermal dilation on reflecting performance was smaller.

The FDTD models were constructed based on the results of our SEM and other papers [8,11,12]. The structural parameters of RSS and BLS were optimized including the layer thickness (Y1), the layers distance (Y2), the adjacent distance between two ridges (T), and structure parameter (θ) as shown in Fig. 1 (c, f). The position of reflecting peak moved from 450 nm to 550 nm with increasing Y1 and Y2 as shown in Fig. 2(e). Moreover, when the 'tree-like' structure transformed into parallel multilayer (pink dot and dash line in Fig. 2e), the reflecting peak was greatly affected. It was also found Y1 = 62 nm, Y2 = 140 nm, and T = 475 nm were the best structural parameters which promised the reflecting peak of RSS model was almost the same with the experimental result. With regard to BLS, the reflecting intensity was mainly depended on θ. The reflecting results of BLS was in a good accordance with the testing result as shown in Fig. 2(g, h) when θ=90°, Y1 = 120 nm, and Y2 = 180 nm. The FDTD results showed the model was logic and correct, although the structural parameters were different with that introduced by Vukusic [11,12]. An almost perfect optical models of RSS and BLS were constructed which could be used to study the thermo-optic properties. Moreover, the iridescent color of RSS and BLS was explainable in terms of multilayer interference as Y1 and Y2 were the factors which determined the position and intensity of reflecting peak.

Thermal dilation of RSS and BLS were calculated and were presented in Fig. 3. It was found Y1 and Y2 of RSS increased after heating, but Y2 of BLS was reduced contrarily. Thus the reflecting spectra were changed as the result of thermal dilation which could be explained theoretically by multilayer interference [8]. Fig. 4(a, b) proved that the drifting tendency of reflecting peak obtained by simulation was similar to the experimental results (Fig. 2a, b). With temperature increasing, the reflecting peaks of RSS and BLS moved towards the larger wavelength gradually. Fig. 4(c, d) showed the thermo-optic performance of BLS was more stable as

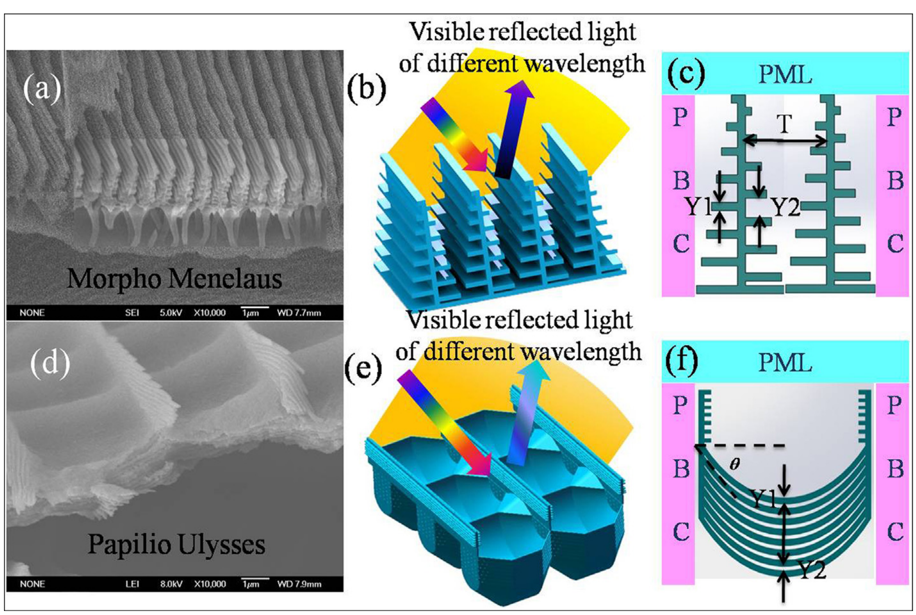

Fig. 1. Iridescent structures of MM and PU: (a) SEM of MM; (b) 3D model of RSS; (c,f) 2D model and boundary conditions in FDTD solutions; (d) SEM of PU; (e) 3D model of BLS.