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Bionic membrane simulating solar spectrum reflection characteristics of natural leaf

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ABSTRACT

Hyperspectral imaging is becoming an important detection method, which can identify the subtle differences between the reflection spectra of a target and its background. Considering that vegetation is one of the most important backgrounds, a bionic membrane containing hygroscopic material and chromium sesquioxide (Cr_2O_3) pigment was prepared to counter the hyperspectral detection through simulating the solar spectrum reflectance of natural leaf. The effects of water and Cr_2O_3 contents on the reflectance of the bionic membrane were discussed, and the absorption and scattering coefficients of the bionic membrane were calculated via a four-flux model to elucidate its reflection mechanism. Based on the obtained absorption and scattering coefficients, the reflectances of the bionic membranes (with a volume fraction of water in the range of 9.75–51.92% during the day time) containing different volume fraction of Cr_2O_3 (f_c) were calculated through the four-flux model. Besides, a military specification of USA was used as the spectrum requirement of the bionic membrane in our work to determine an appropriate Cr_2O_3 content. It was found that when f_c is 1.61%, the reflection spectra of the 3 mm thick bionic membranes can not only meet the military specification but also become opaque, which are capable to camouflage a target.

1. Introduction

Hyperspectral imaging technology is rapidly developing and is becoming an important detection method, which can identify the subtle differences between the reflection spectra of a target and its background. Considering that vegetation is one of the most important environmental backgrounds where a target locates, a bionic membrane which can simulate the solar spectrum reflectance of natural leaf needs to be developed to counter the hyperspectral detection. The spectral reflectance and transmittance of a natural leaf are shown in Fig. 1a [1]. A small reflection peak called the "green apex" appears around 550 nm, which is caused by the characteristic absorptions of pigments, mainly the contribution of chlorophyll [2,3]. The reflectance increases sharply between 680 and 780 nm, forming the "red edge". In the range from 780 to 1300 nm, both the reflectance and transmittance maintain at a high level of approximately 50% as a result of the multiple reflections of porous structure or the scattering of small particles within the leaf [1,4], which is called the "near infrared plateau". Two water absorbing bands appear at 1460 and 1940 nm, due to the absorption of water in the leaf [5,6]. It is worth noting that the reflected radiation of an outdoor object would only be recorded by a hyperspectral imager in the regions of 0.35–1.30 μm, 1.44–1.80 μm and 1.99–2.40 μm due to atmospheric water vapor absorption [7]. Whereas, after obtaining a hyperspectral data, atmospheric calibration would be conducted to obtain the actual reflectance of the object [8]. Therefore, it is necessary to simulate the reflectance of natural leaf over the whole solar spectral range for the bionic membrane.

Researches on the development of optical bionic materials were inspired through understanding of the composition and structure of natural leaf. Zhang and Zhang [9] prepared a bionic cotton fabric dyed with a combination of dyes, and its spectral reflectance curve showed similar characteristics to that of natural leaf between 300 and 1300 nm, as shown by curve b_1 in Fig. 1b. However, it could not imitate the characteristic of water absorption above 1300 nm due to no water accommodated. Based on the composition of angiosperm leaves, Yang et al. [10] designed a bionic material composed of a chlorophyll/polyvinyl alcohol (PVA) film, a sealed bag of polyvinylidene chloride (PVDC) containing water and a piece of paper. Qin et al. [11] developed a poly(urea-formaldehyde) microcapsule containing chlorophyll and water. These above two bionic materials both could simulate the solar spectrum reflectance of natural leaf, as shown by curve b_2 and b_3 in Fig. 1b, respectively. The chlorophyll as an additive for the above bionic materials tended to be photodegraded in vitro, which affected the endurance of the bionic material under sunlight. Considering that water and pigments play crucial roles in the solar spectrum reflectance of

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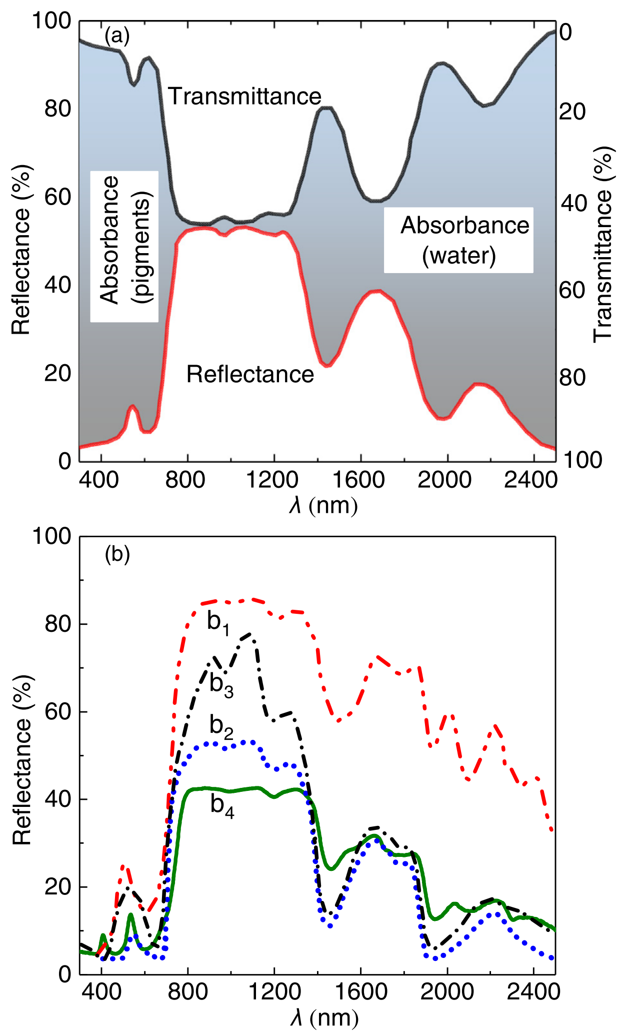

Fig. 1. The spectral reflectance and transmittance of a natural leaf [1] (a) and the spectral reflectances of bionic materials (b): dyed cotton fabric [9] (b_1), the bionic composite material [10] (b_2), the poly(urea-formaldehyde) microcapsule [11] (b_3) and the bionic leaf [12] (b_4).

natural leaf, a bionic leaf containing hygroscopic PVA, lithium chloride (LiCl) and chromium sesquioxide (Cr_2O_3) was prepared in our previous work [12], and its spectral reflectance was similar to that of natural leaf as shown by curve b_4 in Fig. 1b.

However, the reflection mechanism and the optimization of the optical bionic performance for the bionic leaf were not comprehensively explored in our previous work. Therefore, the bionic membranes with different content of Cr_2O_3 were prepared by a solution casting method and their spectral reflectances and transmittances were measured. Based on the above measurements, the absorption and scattering coefficients of the bionic membranes were derived with a four-flux model to illustrate the reflection mechanism. Furthermore, the spectral reflectances of the bionic membranes containing different content of Cr_2O_3 were simulated via the four-flux model, and a spectrum requirement was used for evaluating the optical bionic performance of the bionic membrane to determine an appropriate Cr_2O_3 content.

2. Experiment and model

2.1. Preparation

Considering the key roles of water, pigments, porous structure and small particles in the solar spectrum reflectance of natural leaf, we proposed a bionic membrane containing hygroscopic materials (PVA and LiCl) and Cr_2O_3 particles to imitate the solar spectrum reflectance of natural leaf. PVA has good membrane-forming and mechanical properties, and it can absorb water vapor because of its large quantity of —OH groups [13]. However, PVA membrane tends to swell and even dissolve after absorbing a certain amount of water vapor. Therefore, it must be modified through appropriate methods. In this work, chemical crosslinking was adopted to modify the PVA membrane, and L-malic acid was used as the crosslinking agent. To enhance the hydrophilicity, LiCl which is a highly hydrophilic salt [14] was dispersed in the PVA membrane. Cr_2O_3 which is often mentioned as an infrared-reflective pigment that is useful for simulating the high infrared reflectance of natural leaves [15] was also dispersed in the PVA membrane. The density and particle size of Cr_2O_3 used in our work are 4.4 g/cm^3 and 559 nm, respectively, obtained through pycnometer and SEM analyses of the particles.

The preparation process of the bionic membrane is as follows. A certain amount of PVA 124 powder was dispersed in deionized water and stirred at 90 °C for approximately 2 h to form a PVA solution. A certain amount of cross-linking agent (L-malic acid), anhydrous LiCl and Cr_2O_3 were dispersed in the above PVA solution to form a casting solution by stirring at 70 °C for approximately 0.5 h. Then, the casting solution was placed into an electric thermostatic drying oven (DHG-9101-1SA) for crosslinking between PVA and L-malic acid at 100 °C for 1 h. After that, the crosslinked casting solution was coated on a glass plate and placed into a constant temperature and humidity chamber (STIK CTHI-150B) to form membrane through solvent evaporation at 60 °C and 10% relative humidity for approximately 6 h. The compositions of the casting solution are listed in Table 1.

2.2. Characterization

The directional-hemispherical transmittance and directional-hemispherical reflectance of samples were measured with an integrating sphere attached to a spectrophotometer DUV-3700. The uncertainties of the transmittance and reflectance of the spectrophotometer are 0.4% and 1%, respectively, according to the calibration results. As shown in Fig. 2a, the incident angle was set to 0° to determine the normal incidence transmittance. We also hope to obtain the normal incidence reflectance, whereas, when the incident angle is set to 0° for measuring reflectance, the collimated reflected radiation flux will escape from the light entrance. Therefore, the incident angle was deflected to 8° in our work to obtain the total reflectance composed of the collimated reflectance and diffuse reflectance, as shown in Fig. 2b, which is a standard operation.

Considering that the angiosperms occupying most of the earth's land surface, which affects the camouflage effect of a target, several kinds of angiosperms leaves were chosen and their reflectances were measured. Based on the obtained reflectances, the spectrum requirement of the bionic membrane can be drawn.

The bionic membranes were sorted into two groups. The first group includes the bionic membranes containing different volume fraction of Cr_2O_3 in dry state (oven-dried at 55 °C for 12 h). The other one includes the membranes without Cr_2O_3 in dry state and wet state (kept in a constant temperature and humidity chamber for 12 h at 30 °C and 80% relative humidity). The volume fraction of water absorbed in a wet membrane, f_w, can be defined as

$$f_w = \frac{m_w/\rho_w}{m_{dry}/\rho_{dry} + m_w/\rho_w} \times 100\% \quad (1)$$

where m_{dry} and m_w are the weights of the dry membrane and water absorbed in the membrane, ρ_{dry} and ρ_w are the densities of the dry membrane and water, respectively. The aim of the above grouping