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Design of multi-passband polymer multilayer film and its application in photovoltaic agriculture

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To solve the issue of the contradiction between photovoltaic power generation and plant photosynthesis for sunlight demand, we propose a design method of multi-passband polymer multilayer optical structure. Using polycarbonate (PC) and polymethyl methacrylate (PMMA), two polymer materials with different refractive indices, the passband position and passband bandwidth are calculated and adjusted by the transmission matrix method and TFCalc software. A 450 nm, 660 nm, and 730 nm three-passband filter was realized by superimposing stacks of different band positions. The feasibility of the photovoltaic agriculture was confirmed by the power generation efficiency and the actual plant growth.

Keywords: polymer multilayer film design; multi-passband; photovoltaic power generation; photosynthesis; photovoltaic agriculture.
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1. Introduction

In recent years, photovoltaic agricultural technology has developed rapidly[1,2]. So far, there are two main solutions for photovoltaic agriculture: (1) mosaic solar panels are distributed and installed above the farmland[3]; (2) translucent thin-film solar cells are adopted, by which a part of sunlight can be transmitted[4]. However, the uneven distribution of sunlight and the light qualities of the transmitted sunlight cannot properly meet the requirements of plant photosynthesis, which will destroy the growth conditions of crops. So, these two solutions cannot really solve the issue of contradiction between plant photosynthesis and photovoltaic power generation. Different light qualities have different roles in the process of plant photosynthesis and morphogenesis. Red light and blue light are the most important for plant photosynthesis[5]. Far-red light also affects the morphology and growth of plants in different forms at various stages of plant growth[6].

In this Letter, we propose a promising solution based on spectral separation to select the red, blue, and far-red light from sunlight for photosynthesis of plants, and the rest of the sunlight is used to concentrate on photovoltaic panels to generate electricity. The key of the solution is to design a multi-passband filter film at low cost. The multiplication co-extrusion (MCE) process, which is capable of economically and continuously producing, has been adopted to prepare alternately superimposed multilayer film[7–9]. However, the existing polymer multilayer optical film products are limited to the spectral characteristics of a single passband. The multi-passband filter of the spectrum required for plant photosynthesis including red light, blue light, and far-red light has not been reported yet.

2. Multilayer Stacks Design Method

The film design of polymer multilayer periodic structures should firstly consider the choice of polymer material combination. The refractive indexes of optical polymer materials are generally between 1.4 and 1.6. The greater the difference in refractive index, the easier it is to design a multilayer optical film with higher reflectivity, wider reflection bandwidth, and fewer layers. The polymethyl methacrylate (PMMA, refractive index $n = 1.4$) is often used as a low refractive index material layer. Considering the material cost and the crystallinity of the material, in this study, we choose the amorphous material polycarbonate (PC, $n = 1.6$) as the high refractive index layer. The melt casting characteristics of PC and PMMA are similar, which is conducive to the multilayer co-extrusion process.

For better understanding the effects of microstructure on the optical performance, we use a modified transfer matrix theory to calculate the reflectivity of a non-absorbing multilayer system, taking into account multiple reflections. In the following, we sketch the essential steps of the method in Refs. [10–12].

The reflectance of the multilayer film is given as

$$R = \left[\frac{n_0(Q_{11} + n_{N+1}Q_{12}) - (Q_{21} + n_{N+1}Q_{22})}{n_0(Q_{11} + n_{N+1}Q_{12}) + (Q_{21} + n_{N+1}Q_{22})}\right]^2,$$

where n_0 and n_{N+1} in our case ordinarily correspond to 1.0 (the refractive index of air).

The MCE process usually adopts equal division and multiplication to obtain a film structure of equal thickness period. The spectral characteristics of the Bragg reflective film with a periodic structure of equal thickness only have a reflection band with a single central wavelength, and the reflection bandwidth is limited. As shown in Fig. 1(a), using PC and PMMA as the material combination, and 410 nm as the reference wavelength, the simulation by TFCalc shows that the reflectivity of the 128-layer multilayer film is almost close to 100%. Due to the small difference in refractive index between the two materials, the reflection bandwidth is only about 20 nm.

In order to realize the design of complex multi-passband optical film system, it is necessary to obtain a series of high-reflection films with different passband positions and wider reflection bandwidth.

Figure 1(b) shows the method of broadening the reflection bandwidth. Take 64[HL] (H = PC, L = PMMA) as the basic film stack1 with a film stack of equal thickness period (410 nm as the reference wavelength). Stack2, which is 1.04 times thicker than stack1, has a center wavelength of 430 nm and the same bandwidth as stack1. When stack2 and stack1 are superimposed together, the bandwidth is doubled. Using more film stacks can achieve an unequal thickness periodic structure with stack thickness gradient.

Polymer film can be stretched and thinned under the glass transition temperature, so the different passband positions and the width of the reflection bandwidth can be adjusted arbitrarily. As shown in Fig. 2, by superimposing stacks with different passband positions, when the short cut-off and long cut-off of each high-reflection band avoid reflections in the 450 nm, 660 nm, and 730 nm bands, a three-passband polymer multilayer optical film can be obtained. As shown in Fig. 3, this film design can accurately and selectively transmit the red, blue, and

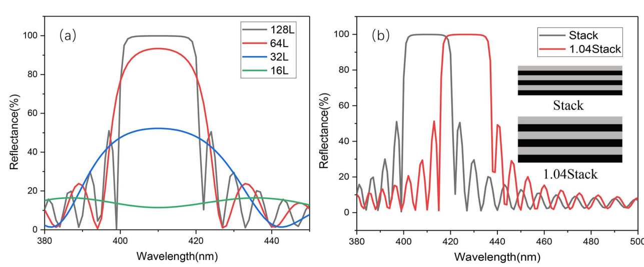

Fig. 1. Broadening of reflection bandwidth: (a) reflectivity of different layers of PC/PMMA multilayer film; (b) reflectance spectra of periodic films with different thicknesses.

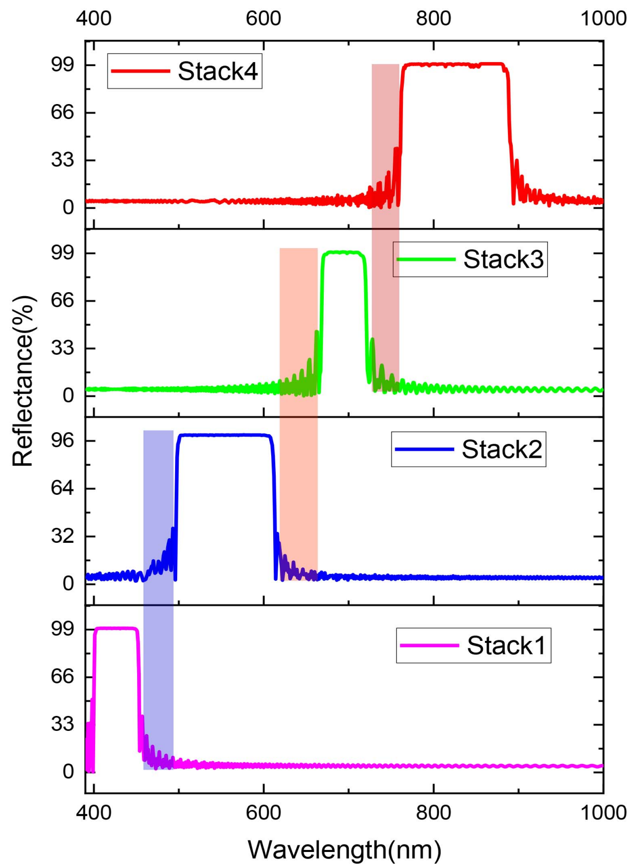

Fig. 2. Superimposing of film stacks at different passband positions.

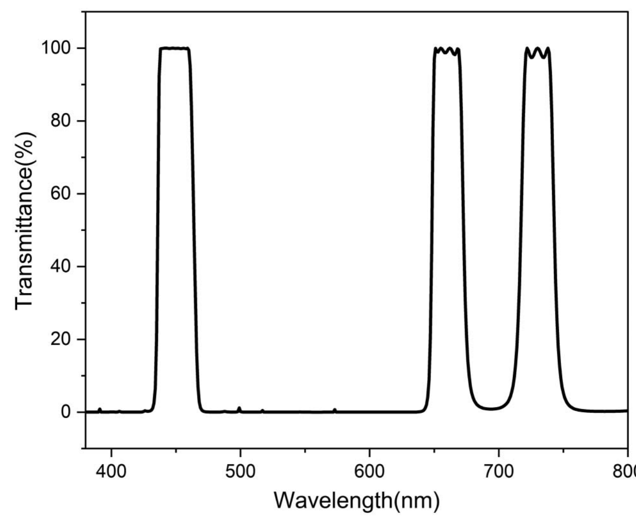

Fig. 3. Three-passband multilayer film suitable for plant photosynthesis.

far-red light in the sunlight, which can meet the light quality conditions required by plant photosynthesis.

3. Results and Discussion

Low-cost polymer multilayer optical films are economically feasible for high-value-added photovoltaic agricultural systems.

Limited by the experimental conditions, in this Letter, we select two single-passband polymer multilayer optical film products (Filter A and Filter B) produced by 3M company with different bandpass positions for splicing to obtain a double-passband polymer multilayer optical film (Filter C), which are shown in Fig. 4. This transmission spectrum of Filter C satisfies all of the light bands required for plant growth. Obviously, it can be seen that the transmission bandwidth of Filter C covers 545–792 nm, which is relatively "surplus" for the red and far-red light required for plant photosynthesis. From the perspective of comprehensive utilization of solar energy, the photovoltaic agricultural system only needs to accurately transmit 450 nm, 660 nm, and 730 nm, and the rest of the bands of light can be used to collect and generate more electricity. Our team has built a 640-layer polymer multilayer optical film co-extrusion casting experiment platform and unidirectional stretching device. Through process design and optimization, it is expected to obtain a spectroscopic film that is more suitable for plant photosynthesis.

The demonstration system of the photovoltaic agricultural system was constructed using a double-passband polymer optical film. Since the incident light angle of sunlight changes every day, the incident light angle will have a blue shift effect on the spectral characteristics of the multilayer optical film. When the incident angle is 40°, the center wavelength position of the reflection band blue shifts by about 50 nm. Therefore, in this application scenario, the trough-type low-power concentrator system needs to adopt a dual-axis sun tracking system to maintain the vertical incidence of sunlight.

As shown in Fig. 5, since the relative spectral response of the crystalline silicon solar cell in the short-wavelength band of blue and red light is low, the blue and red light are separated and transmitted for the photosynthesis of plants, which has little effect on photovoltaic power generation efficiency. Sonneveld *et al.*[13,14] adopted a near-infrared reflective film to spectrally separate sunlight, and they built a photovoltaic agricultural system. Since most of the sunlight is transmitted, the photovoltaic power generation efficiency is only 3%. In contrast, we designed to selectively reflect sunlight in the green light and near-infrared bands, and the power generation efficiency was significantly increased to 9%. The income of photovoltaic power generation varies with geographical factors such as sunshine and temperature in different regions, as well as the difference in electricity price subsidies. Taking the Anhui region as an example, one hectare of farmland can be installed with 0.5 MW photovoltaic power plants, and its annual power generation revenue is about $48,000. In addition, under our agricultural photovoltaic system, the income from growing tobacco is approximately $4100. Therefore, compared with ordinary photovoltaic agricultural farmland, the comprehensive income of our system can be increased by about 8%. The experimental results show that the solution of the photovoltaic agricultural system we designed can realize the comprehensive utilization of solar energy. Since most of the solar radiation is reflected, shade tolerant crops have a more relaxed light environment, and photosynthetic efficiency can be greatly improved. At the same time, in the hot summer, shaded by our photovoltaic agricultural system, the plant leaf surface water transpiration and evaporation rate significantly decline, which also plays a role in reducing leaf temperature and saving irrigation water. Compared with conventional field

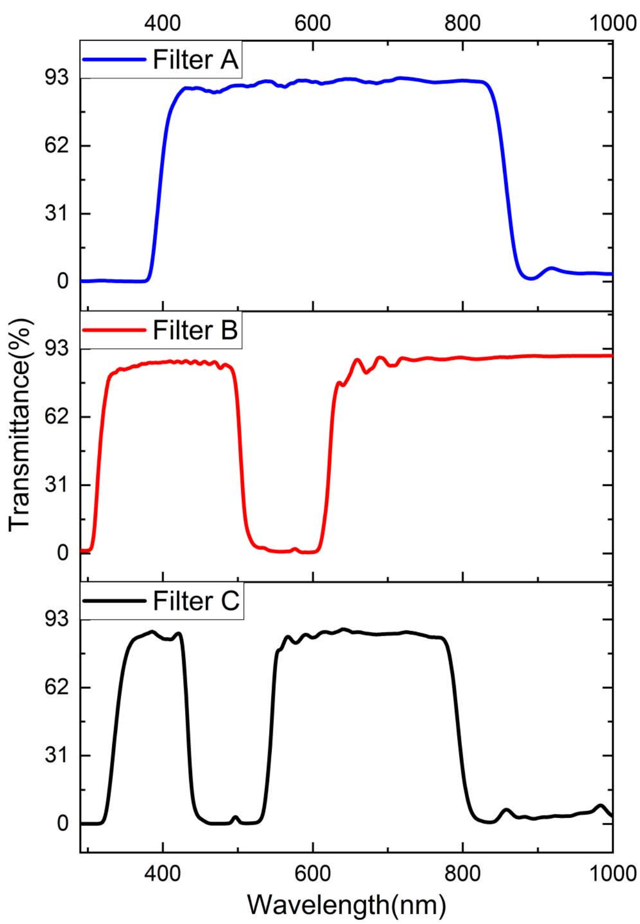

Fig. 4. Spectrum of the double-passband polymer multilayer optical film.

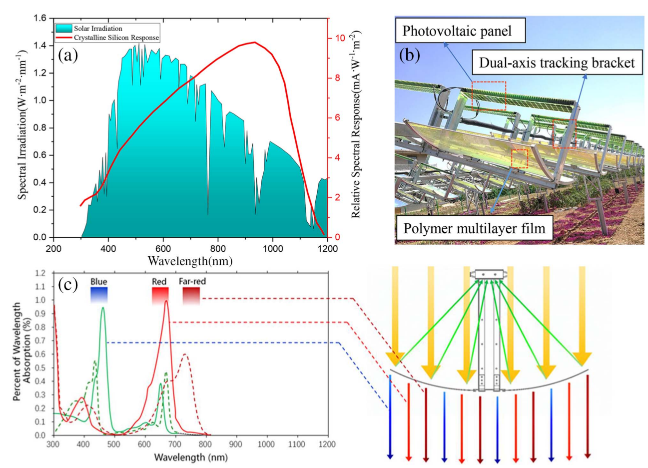

Fig. 5. Multi-passband filter film applied to the photovoltaic agricultural system: (a) solar radiation and spectral response of crystalline silicon cells; (b) biaxial tracking photovoltaic agricultural system; (c) spectra required for plant photosynthesis.

planting conditions, the soil water evaporation rate under this photovoltaic agricultural system is reduced by 25%.

Polymer materials generally have poor UV resistance and have a short service life when used outdoors for a long time. The UV band can be reflected by adjusting the thickness of the film period. In addition to the first-order reflection, a polymer multilayer film can exhibit higher-order reflections. The wavelengths at which reflections of the various orders appear are given by[15]

$$\lambda_M = \frac{2}{M}(n_1 d_1 + n_2 d_2) = \frac{\lambda_0}{M},$$

where λ_M is the Mth-order reflection. Although the spectral locations of the various orders are determined entirely by the sum of optical thicknesses ($n_i d_i$) of the two adjacent layers, the relative intensities of the various orders are strongly dependent upon the ratio between the two optical thicknesses. For films of equal optical thicknesses, the even orders are suppressed (zero reflectance), and the odd orders are at maximum reflectance. For example, if the first-order reflected wavelength $\lambda_0 = 900\,\mathrm{nm}$, there would be high reflection at $\lambda_0/3 = 300\,\mathrm{nm}$. Therefore, the polymer multilayer film used in this solution has good UV resistance. The polymer multilayer film is actually used on the back of the trough-type condenser glass, and the glass itself also blocks part of the UV rays, so the film can be used outdoors for a long time.

4. Conclusion

A 450 nm, 660 nm, and 730 nm three-passband filter was realized by superimposing stacks of different band positions. Using the design method in this Letter, the selective transmission spectrum of the polymer multilayer optical film can be arbitrarily adjusted. The feasibility of photovoltaic agriculture was confirmed by the power generation efficiency and actual plant growth. The polymer filter has an obvious low-cost advantage; not only can it be used in photovoltaic agricultural systems to efficiently use solar energy, but it can also be used in fields such as heat insulation, anti-UV, and infrared shielding.

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