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Featured Letter

Enhancement of angular color uniformity of remote-phosphor-converted light-emitting diodes by electrospun-nanofiber diffusing films

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ABSTRACT

We propose electrospun-nanofiber diffusing films to enhance the angular color uniformity (ACU) of remote-phosphor-converted light-emitting diodes (RPC-LEDs). Poly(vinylidene fluoride) electrospun nanofibers/acrylic composite films with different nanofiber thicknesses are investigated. An optimal composite film is obtained based on the balance between the ACU enhancement and luminous flux reduction, which can be applied to RPC-LEDs with different correlated color temperatures (CCTs) to enhance the ACU with a small luminous-flux loss, particularly at higher CCTs. Therefore, the composite films can effectively enhance the ACU of RPC-LEDs while maintaining a high luminous flux.

1. Introduction

White-light-emitting diodes (WLEDs), regarded as energy-efficient environment-friendly long-life-time lighting sources, have been extensively investigated to replace traditional lighting sources [1]. The most common method to generate white light is to combine blue LEDs with yellow phosphor [2]. Remote-phosphor (RP) structure has been invented to achieve a high luminous efficacy of WLEDs; however, these remote-phosphor-converted LEDs (RPC-LEDs) exhibit a poor angular color uniformity (ACU) particularly for planar RP films [3]. Various methods have been proposed to address this issue, including incorporation of submicron particles and use of diffusing sheets, which reduce the luminous flux [4,5]. Distributed Bragg reflector [6] and partially patterned sapphire [7] were coated with RP to improve the ACU; however, they are challenging to fabricate. Therefore, it is challenging to improve the ACU of RPC-LEDs while maintaining a high luminous flux.

Recently, electrospun nanofibers have been applied in optical fields [8], formed into films as a high-reflective cup to improve the light efficiency for instance [9], which are limited to the lamp structure. For general lightings, the use of a diffusing film is the most common approach for performance improvement [5]. The formation of electrospun nanofibers into a diffusing element for RPC-LEDs has not been reported. In this study, poly(vinylidene fluoride) (PVDF) was electrospun to nanofibers; acrylic was then spin-coated on them to fabricate PVDF/acrylic composite films [10]. Their optical characteristics were studied and optimized to obtain a high ACU of RPC-LEDs while maintaining their high luminous flux in different lighting systems.

2. Experimental methods

PVDF is selected as the electrospun material owing to its low refractive index (RI ~ 1.41). PVDF pellets (M_w = 530,000, Sigma-Aldrich) were dissolved in a mixture of acetone and dimethylformamide (volume ratio: 3:2) to obtain a 0.15-g/ml solution (viscosity: 510 mPa·s). The nanofibers were collected to a glass (diameter: 30 mm) using our home-made far-field electrospinning setup (Fig. 1(a)). The electrospinning parameters are: applied voltage: 16 kV, working distance: 16 cm, and flow rate: 0.16 ml/h. The acrylic (named 80582, Guangzhou Changxing Fine Coating), an ultraviolet-(UV)-curable resin (molecular formula: $(C_3H_4O_2)_n$), was then spin-coated on the nanofiber and cured for 15 s under a mercury lamp (1 kW, 365 nm) to fabricate the composite films. The fiber morphologies were characterized using a field-emission scanning electron microscope (FEG-SEM, Zeiss® Merlin). The thickness was measured using a super-depth microscope (KEYENCE VHC-2000C, Japan). The diffuse transmittance and haze were

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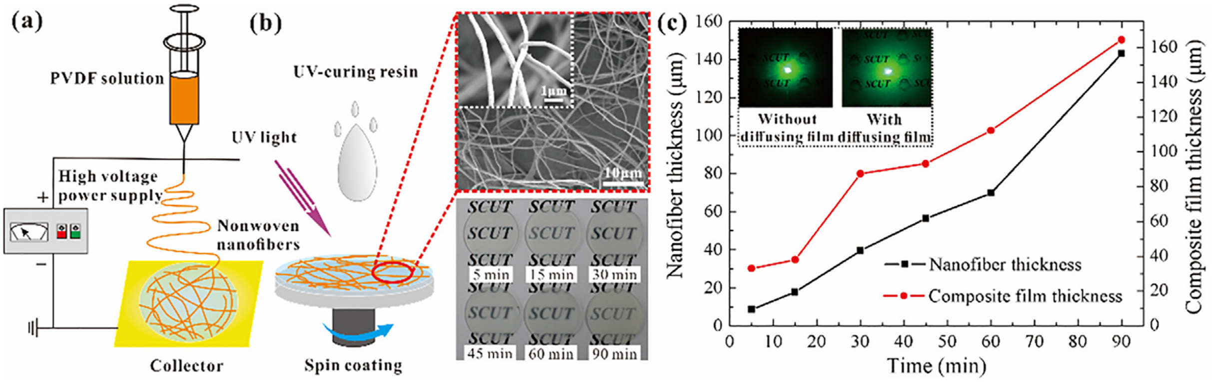

Fig. 1. (a) Schematic of the electrospinning. (b) Composite-film preparation. (c) Nanofiber and composite-film thicknesses as a function of the time. The inset shows the green-laser-light spots.

investigated using an UV–visible-light spectrophotometer (dual-beam UV–VIS spectrophotometer TU-1901).

3. Results and discussions

Fig. 1(b) shows the randomly oriented fibers (average diameter: 300 ± 29 nm) forming a non-woven structure. The nanofiber thickness increases with the deposition time (Fig. 1(c)), from 8.6 μm to 142.9 μm; the composite-film thickness increases from 33 μm to 164.4 μm. The inset shows the high diffusion ability of the composite films, whose diffuse transmittance and haze were measured (Fig. 2). With the increase of the nanofiber thickness, the diffuse transmittance slightly decreases while the haze considerably increases, as the nanofibers act as light-diffusion materials [11]; their concentration increases from 1.19% to 6.81%, depending on the nanofiber thickness (Fig. 3(b)). The high-porosity staggered structure [9], and interfaces with mismatched RIs of the fiber and acrylic cause high reflectance and refraction [12]. An RPC-LED device (inset of Fig. 3(a)) was employed to study the optical properties of various composite films. The phosphor film was separated from a blue-LED (3535, Foshan Nation Star) by a black polytetrafluoroethylene tube. RP films with different phosphor ratios were combined to various composite films for similar CCTs (~4500 K). The luminous flux and CCT deviation (ΔCCT, equal to the difference between the maximum and minimum CCTs in the range of −80° to 80°) are shown in Fig. 3(a). Compared to the reference, the luminous flux decreases gradually, while ΔCCT initially slightly increases and then rapidly decreases with the increase of the nanofiber thickness. An optimal factor *F* [13] is defined corresponding to the optimal composite film with a good balance between the transmittance and haze. The CCT-deviation improvement ratio (ρ_{CCT}) and luminous-flux decrement ratio (σ_{lm}) of the RPC-LEDs are analyzed using the following equation:

$$F = \rho_{CCT}/\sigma_{lm}$$

A larger *F* implies a better RPC-LED's optical performance (high ACU and luminous flux). The composite film with a nanofiber thickness of 39.5 μm (marked as optimal film) exhibits the best optical performance among the samples (Fig. 3(b)). The ACU improvement is mainly attributed to the scattering characteristics of the composite films. More blue light is backscattered at the phosphor and re-utilized to the conversion of yellow light; however, it simultaneously leads to a backscattering-light-absorption loss, leading to a small luminous-flux reduction. The reduction increases with the nanofiber-film thickness, which is a more significant factor than the ACU enhancement. The optimal film exhibits a ΔCCT of 490 K (decrease of 51.61%) with a luminous loss of only 3.16% at 350 mA. In comparison, Ding et al. [13] demonstrated a micropatterned array film with a ΔCCT decrease of 62.83%, while maintaining 83% of the light output power. Consequently, the conventional RP structure has a worse color-mixing ability; the optimal film exhibits a superior performance with a high ACU. In the following experiments, the optimal film maintaining a diffuse transmittance of 78.48% and haze of 91.58% in the visible-light range is selected for lamp applications, which has not been reported for RPC-LEDs [14].

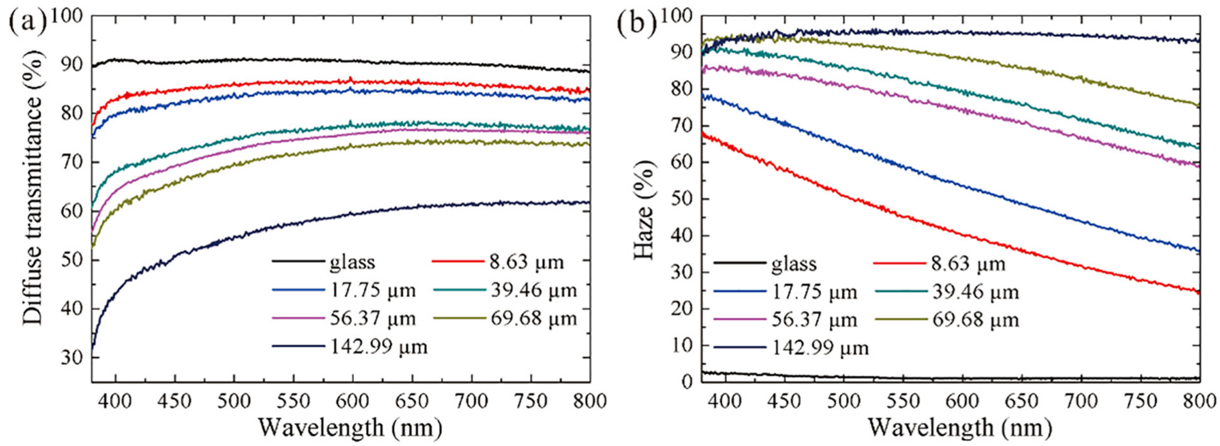

Fig. 2. (a) Diffuse transmittance and (b) haze of the composite films.