Advanced Nanocomposite Materials Tailored to Solid-State Lighting Applications

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ABSTRACT

Nanofibers are materials with nanoscale diameters and macro-scale lengths. When formed into non-woven fabrics, polymer nanofibers become mass producible materials with unique optical properties that can be used in many different applications. By combining nanofibers with luminescent nanoparticles to form photoluminescent nanofiber substrates, a unique nanocomposite is created that provides multiple benefits to energy efficient lighting devices. Examples of the use of these materials in solid-state lighting devices are presented, along with a discussion of the performance of these nanocomposites in lighting applications.

Keywords: nanofiber, quantum dot, phosphor, lighting, photoluminescence

1 INTRODUCTION

Polymeric nanofibers are nanoscale materials whose properties can be adjusted to provide desirable light management solutions across the visible spectrum. While their diameters are on the order of 100 to 1000 nm, the length of polymer nanofibers can exceed 1 cm. Typically, nanofibers are formed into a non-woven fabric using the process of electrospinning, which can be performed in high volumes using a roll-to-roll process [1].

Nanofibers and nanocomposites made from nanofibers are emerging as a key enabling technology for the next generation of high efficiency lighting devices. The emergence of these materials in lighting applications is driven by the fact that nanofiber substrates possess unique optical properties. For example, the reflectance and transmittance of nanofiber materials can be tailored by manipulation of several parameters including the nanoscale features of the fabric, fiber spacing, and substrate thickness [2].

2 NANOFIBER FABRICATION

Control of the electrospinning formulation is critical to achieving the required nanofiber morphologies required in the nanofibers used for SSL. Single solvent systems often produce cylindrical nanofibers, whereas multi-component solvent systems typically produce a variety of surface morphologies including surface pores [3]. Specifically, since the light scattering cross-section of a feature determines the efficiency that light of a particular wavelength is scattered, being able to control the size of the scattering site (i.e., fiber diameter, pore diameter, width, length, etc.) is critical to achieving the optical properties necessary for SSL applications. Examples of smooth and porous nanofiber structures and a discussion of their respective optical properties can be found elsewhere [4].

A critical element of the optical properties of nanofibers is their ability to spread light evenly and provide uniform light intensity (i.e., light diffusion). Optimizing this characteristic in nanofibers involves examining the light diffusion properties of the substrates both in transmission and reflection modes of operation. To perform this measurement, an Eldim Conoscope, which measures light intensity as a function of exit angle from a surface, was used. In this test, the nanofiber substrates were illuminated by light from two different commercial high brightness, white light emitting diodes (HB-LED), and the performance of three different nanofiber samples was measured. Two paper samples were used for comparison with the nanofiber materials; one paper was relatively dense and the other paper had an open arrangement of fibers. The nanofiber samples showed strongly differing distributions of light scattering depending on preparation conditions. Under certain fabrication conditions (e.g., dense thick materials), the nanofiber structure exhibited excellent light diffusion, which is desirable for general illumination applications to ensure even lighting across planar lighting structures. An example of a nanofiber fabric displaying good light diffusion characteristics is shown in **Figure 1**.

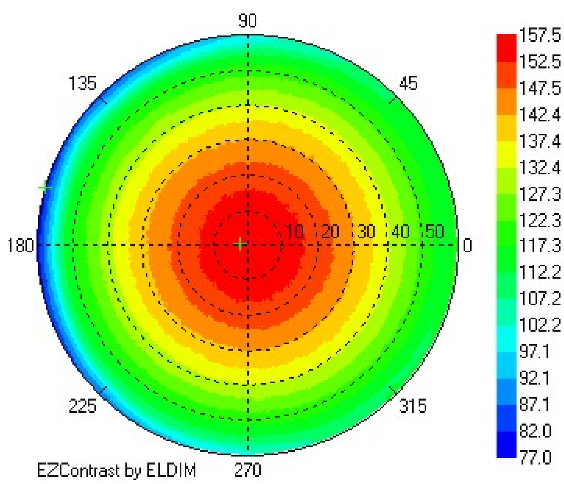

Figure 1: Plot of the light diffusion characteristics of a nanofiber structure when illuminated by a commercial HB-LED. The symmetry and gradual decline in light intensity, on progressing from the center outward, provides quantitative evidence that this nanofiber structure is a good diffuser of visible light.

3 PLN FORMATION

A nanocomposite formed by combining luminescent particles (e.g., quantum dots) and nanofibers serves as a high performance material with exceptional properties for lighting applications. Through judicious choice of fabrication parameters, this nanocomposite (hereafter termed photoluminescent nanofiber (PLN)) has been used to fabricate luminaire prototypes with luminous efficacies in excess of 50 lumens/watt and color rendering indices greater than 90. In order to achieve this level of performance, the PLN material must efficiently convert incident blue light from a light emitting diode (LED) into broad spectrum visible light.

In addition to the optical properties of the nanofibers, the performance of the luminescent particles chosen for inclusion in the PLN is also critically important in determining the overall efficiency of the nanocomposite as a light source. The desired luminescent particles must balance a number of variables including:

- Absorption spectrum
- Emission spectrum (both emission peak and peak width)
- Emission efficiency as given by quantum efficiency [5]
- Relative concentrations of different luminescent particles
- Ability to be applied to the nanofiber
- Long-term stability

The absorption spectrum of the luminescent particles is critical since the PLN structure must efficiently absorb the pump wavelength (e.g., emissions from a blue LED in this instance) and exhibit minimal parasitic absorption for emissions from other luminescent particles. In order to provide high quality white light, luminescent particles should be chosen that have an emission spectra that closely matches the photoptic sensitivity of the human eye. This can be achieved by combining emissions from one or more blue LEDs with that from a yellow emitter (e.g., cerium-doped yttrium aluminum garnet), but the color rendering properties of the light source will improve as more visible wavelengths are added. A combination of blue, green, and red is typically the minimum needed for a white light source with good color rendering properties. The blue light can be supplied by a pump LED, while green and red emissions can be obtained from the PLNs. The quantum efficiency of the luminescent materials is critically important to the overall efficiency of the device, and it is desirable to use luminescent particles with quantum efficiencies in excess of 0.80 in lighting applications.

Key among the fabrication parameters for the nanocomposites is the nature and concentration of the luminescent particles. When combined in the proper proportions, luminescent particles of different emission characteristics can be incorporated into the PLN nanocomposite and virtually any point on the chromaticity diagram can be produced with the appropriate pump wavelength (**Figure 2**). The luminescent particles used to make PLN G1 and PLN G2 in Figure 2 exhibited the same peak maximum in their emission spectra, but had different peak widths, which changed the color emitted by the PLN. With this knowledge, blending the luminescent particles in the appropriate proportions can produce lighting devices exhibiting high color rendering properties (CRI > 85) at pre-determined colors ranging from warm white to cool white. However, care must be taken in forming the nanocomposite, as some luminescent nanoparticles such as quantum dots will have their fluorescence properties quenched under certain processing conditions. Avoiding such conditions is critical to maintaining high quantum efficiencies.

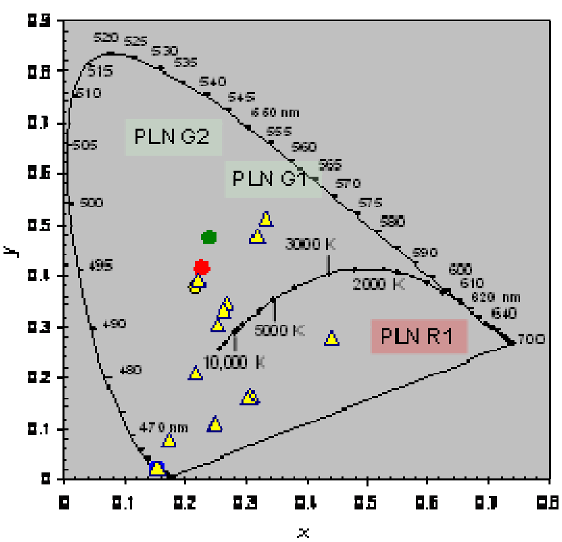

Figure 2: Chromaticity coordinate plot of different PLN formulations demonstrating the ability of chosen PLN structures to produce a multitude of colors when mixed appropriately.

4 NANOFIBER LIGHTING DEVICES

PLNs can be incorporated into lighting structures such as lenses and encapsulants that have high transmittance and will simultaneously provide light diffusion and optical filtering. In addition, the nanoscale structure of PLNs can be manipulated to be compatible with entirely new lighting device structures relying on the diffuse reflectance of light. This affords the opportunity to incorporate the PLN nanocomposite into various elements of the lighting device. The light output from a representative lighting device made using PLNs is shown in **Figure 3**.

The luminous flux produced by such a lighting device can be measured with a fiber optic spectrometer and an integrating sphere using standard testing protocols such as LM-79. A representative luminous flux spectrum produced by a PLN light source is provided in **Figure 4**.

Figure 3: Light produced by a downlight prototype containing, a customized PLN and high reflectance nanofiber lining. The device is powered by a blue LED and photoluminescent emissions from the PLN provide full spectrum color. The spectral luminous flux produced by this device is given in Figure 4.

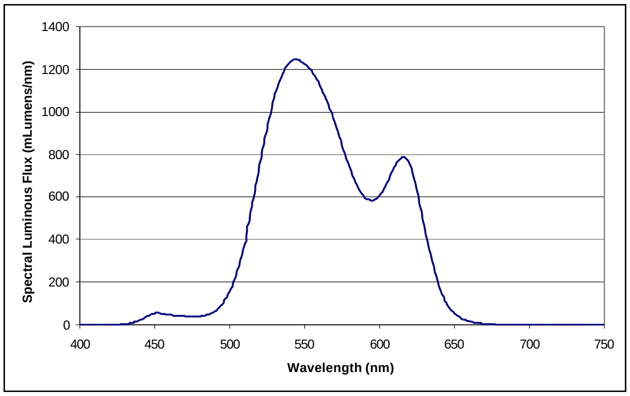

Figure 4: Spectral luminous flux obtained from a PLN-based light source optically pumped by a blue LED. The light source has a CCT value of 3,900 K and a CRI value of 92. The luminous efficacy of this light source exceeded 55 lumens/watt at LED drive currents of 200 mA.

5 CONCLUSIONS

Nanofibers are an emerging technology for use in energy efficient solid-state lighting devices. Nanofibers and PLNs formed by combining nanofibers and luminescent particles can provide a range of utility for lighting devices, including providing high efficiency down-conversion of LED wavelengths to full spectrum white light and providing mass producible, cost-effective solutions for light management across the visible spectrum.

6 ACKNOWLEDGEMENTS

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