Photoluminescent Nanofibers for Solid-State Lighting Applications

L. Davis, L. Han, P. Hoertz, K. Guzan, K. Mills, H.Walls, T. Walker, and D. Magnus-Aryitey
RTI International, Research Triangle Park, NC, USA

Abstract

Photoluminescent nanofibers (PLNs) can be formed by combining electrospun polymeric nanofibers and luminescent particles such as quantum dots (QDs). The physical properties of PLNs are dependent upon many different nanoscale parameters associated with the nanofiber, the luminescent particles, and their interactions. By understanding and manipulating these properties, the performance of the resulting optical structure can be tailored for desired end-use applications. For example, the quantum efficiency of QDs in the PLN structure depends upon multiple parameters including QD chemistry, the method of forming the PLN nanocomposites, and preventing agglomeration of the QD particles. This is especially important in solution-based electrospinning environments where some common solvents may have a detrimental effect on the performance of the PLN. With the proper control of these parameters, high quantum efficiencies can be readily obtained for PLNs. Achieving high quantum efficiencies is critical in applications such as solid-state lighting (SSL), where PLNs are an effective secondary conversion material for producing white light. Methods of optimizing the performance of PLNs through nanoscale manipulation of the nanofiber are discussed, along with guidelines for tailoring the performance of nanofibers and QDs for application-specific requirements.

Electrospinning

Polymer nanofibers are macro-sized objects with nanoscale features. The length (>> microns) of the nanofibers imparts macro-scale properties, while their diameter (50 nm–500 nm) imparts nanomaterial behavior. In addition, other nanoscale features such as surface pores or nanoparticles (e.g., luminescent quantum dots [QDs]) can be incorporated into the nanofiber to provide special physical and optical properties.

Nanofibers are typically formed using the process of electrospinning, which involves applying a high voltage to an electrode in contact with a reservoir of polymer solution.

Figure 1. *Size comparison of a human hair with polymeric nanofibers.*

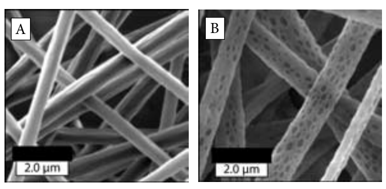


Figure 2. *SEM images of (A) smooth PMMA nanofibers and (B) porous PMMA nanofibers produced through electrospinning.*

As the solution flows to the electrode, the high electric field deforms each drop of the polymer solution into a conical shape known as a Taylor cone. Above a threshold limit, the electrical forces overcome the surface tension of the solution, and a fine, charged jet is ejected from the electrode and ultimately deposits nanofibers on a grounded substrate.

In SSL applications, we have found that nanofiber mats serve the following functions:

- Provide optical filtering of the pump radiation
- Diffuse light emitted by the structure
- Provide a convenient, mass-producible substrate for handling nanoparticles
- Conform to geometries imposed by the light fixture
- Protect from inadvertent releases of nanoparticles.

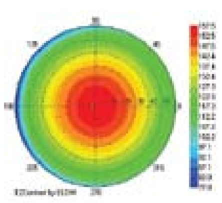


Figure 3. *Light diffusion characteristics of a nanofiber structure when illuminated by a commercial LED. The symmetry and gradual decline in light intensity, progressing from the center outward, provides quantitative evidence that this nanofiber structure is a good diffuser of visible light.*

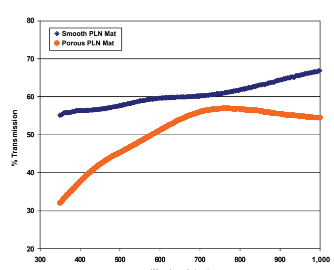


Figure 4. *Transmittance profiles of smooth and porous nanofibers show that RTI has the capability to tailor the optical properties of the SSL devices via fiber surface morphology.*

Quantum Dots

Figure 5. *The emission color of a QD is size-dependent, with green being the color of the smallest QDs. RTI has formulated custom QD solutions for SSL nanofiber coating applications.*

The quantum dots used in the spray coating solution have the following properties:

- The QD consists of a semiconducting CdSe core that absorbs short wavelengths and emits longer wavelengths. The emission color depends on the size of this core.
- A ZnS shell surrounds the core and provides environmental stability.
- A long-chain amine coordination sphere is attached to the ZnS shell to provide compatibility with various solvents and polymers.

QDs can be coated on the surface of the nanofibers using various methods such as spray coating and dip coating. For SSL applications, we have determined that a modified spray coating method produces the best properties in the PLN.

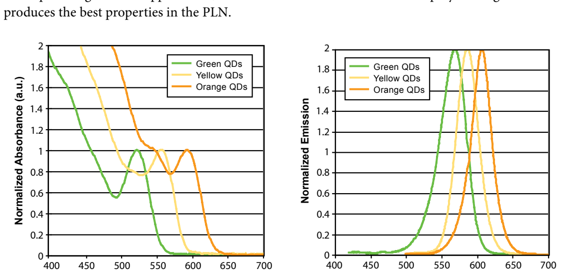


Figure 6. *Normalized absorbance and emission spectra of the CdSe/ZnS core-shell QDs used in this project.*

Photoluminescent Nanofibers (PLNs)

PLNs are a nanocomposite formed by combining nanofibers with luminescent particles such as QDs. Some solvents used in electrospinning lower the quantum efficiency of QDs when incorporated in the interior of the nanofiber in a bulk PLN structure. Separating the electrospinning and QD application processes enables each to be optimized separately. The resulting surface PLN produced by coating nanofibers was found to exhibit the highest quantum efficiency as measured by the DILM Method [1].

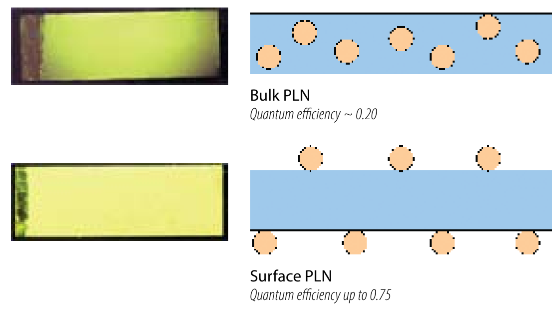
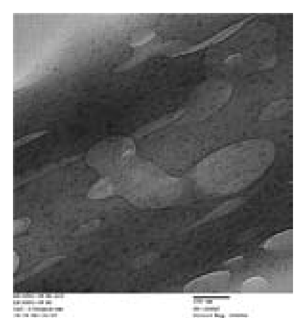


Figure 7. *Comparison of the intensity of light emission from bulk PLNs (in which the QDs reside in the nanofiber interior) to surface PLNs (in which the QDs reside on the nanofiber surface).*

Figure 8. *Transmission electron microscope image of a surface PLN showing low nanoparticle agglomeration.*



A modified spray coating technique was developed to produce even coatings of QDs or other luminescent nanoparticles on nanofiber substrates. Each QD ink formulation must be customized to the chemistry of each QD. The advantages of spray coating technologies for this application include:

- The method does not contact the nanofibers and does not damage them.
- Different patterns can be quickly applied and tested.
- Multiple layers and geometries can be used to control the quantity of QDs deposited.

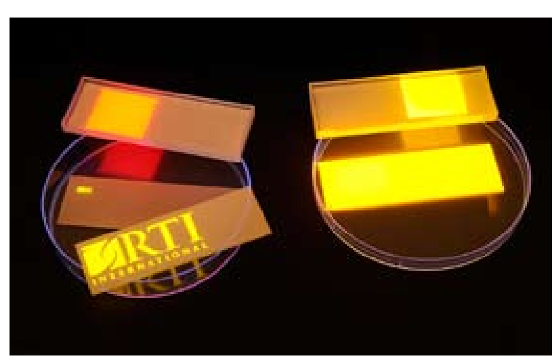
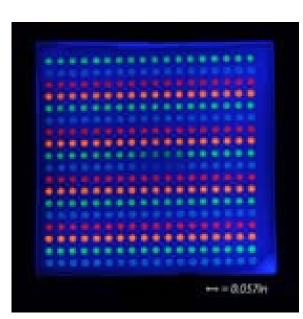
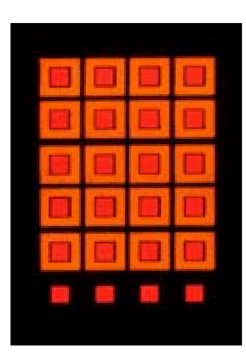


Figure 9. *A variety of patterns ranging in size from very small to coverage of the entire substrate are being produced with the current RTI technology of spray coating QDs onto nanofiber mats.*





Lighting Applications of PLNs

PLNs offer multiple benefits to lighting applications including:

- Providing cost-effective, diffuse, high reflectance light management across the visible spectrum.
- Producing appropriate color balance for lighting with high color rendering indices.
- Efficiently converting the pump wavelength to broad-spectrum visible radiation.
- Conforming to geometries imposed by the light fixture, enabling new lighting designs.
- Enabling the fabrication of mass-producible substrates for handling luminescent particles.

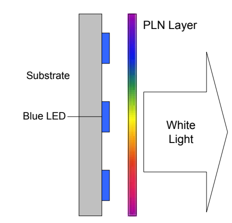
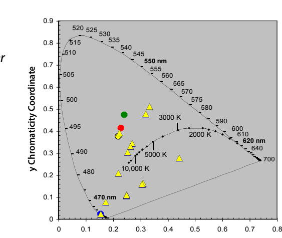


Figure 10. *Schematic diagram of the basic architecture of a lighting system employing PLN technology. Blue LEDs excite the luminescent particles in the PLNs, resulting in broadband color emissions. Through proper choice of excitation and emission color power levels, white light is produced.*

Figure 11. *Combining red and green PLNs and exciting them with a blue (450 nm) LED produces an intense white light source that can be used for general illumination. This lighting device has a correlated color temperature of 3,850 K and a color rendering index of 92.*

Figure 12. *Through a judicious choice of nanofiber properties and luminescent particle coatings, virtually any point on the chromaticity axis can be produced. In this example, a blue (450 nm) LED is used to pump green and red PLNs to produce various colors.*



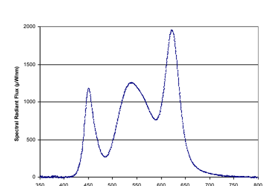


Figure 13. *Typical spectral radiant flux obtained using the PLN technology. This light source was a neutral white color.*

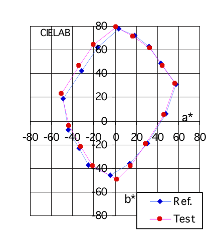


Figure 14. *The similarity between the PLN test light and the reference standard demonstrates that highly accurate color rendering is possible using PLN technology.*

Table 1. Comparison of lighting device incorporating RTI's nanofiber technology with conventional lighting devices

	Incandescent	Fluorescent	RTI's Nanofibers
Efficiency	10 Lumen/Watt	55 Lumen/Watt	>55 Lumen/Watt
Heat Production		—	
Color Quality			
Glare/Eye Strain			
Dimmability			

Excellent performance
Moderate performance
Lower than desired performance

Conclusions

PLNs are a new class of materials for SSL applications that can be created by combining polymeric nanofibers and luminescent particles such as QDs. When dispersed across a flexible panel, PLNs are able to diffuse light and provide panel lighting from inorganic LEDs. The polymeric nature of the PLNs imparts the ability to conform to the luminaire design and also provides a mass-producible substrate for housing QDs. Application of QDs to PLNs can be accomplished using common liquid-phase coating methods such as spray coating. The composition of the coating formulations will vary depending upon each QD, and each formulation must be optimized to maintain high quantum efficiencies and acceptable adhesion. PLNs have been demonstrated to produce high luminous efficacy (>50 lumen/watt) lighting prototypes with excellent color rendering properties.

Acknowledgments

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References

1. International Electrotechnical Commission (IEC) Standard 62607-3-1, Nanomanufacturing: Key Control Characteristics of Luminescent Nanomaterials: Quantum Efficiency, in preparation.

Contact Information

Lynn Davis, PhD
Phone: 919.316.3325
E-mail: ldavis@rti.org

RTI International
3040 Cornwallis Road, PO Box 12194
Research Triangle Park, NC 27709-2194
www.rti.org