Final Technical Report

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Solid State Lighting

Recovery Act: Low-Cost, Highly Lambertian Reflector Composite For Improved LED Fixture Efficiency and Lifetime

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A. Executive Summary

The overall objective of the program was to demonstrate a 98% or greater reflective, highly diffuse, low-cost composite material that significantly improves luminaire efficiency, is able to withstand 50,000 hours or greater luminaire operation under expected LED system thermal and environmental operating extremes and meets the cost targets required to be an effective commercial solution for the Solid State Lighting industry.

This project met most of the goals defined and contributed to the understanding of high reflectance, white coatings. Research under this program increased the understanding of coatings development using particle size reduction techniques and preparation of coating solutions with a broad range of particle types. The research explored scale-up of coating systems and generated understanding of processing required for high volume manufacturing applications. The work demonstrated how coating formulation and application technique can translate to material durability and LED system lifetime. The research also demonstrated improvements in lighting efficiency to be gained using high reflectance white coatings.

“How the project is otherwise of benefit to the public”

This project:

- Improved technical understanding of how to manufacture and apply high reflectance white coatings
- Technology is to be used in LED lighting systems that will directly contribute to improved energy efficiency for consumers and the public, lower overall costs for LED systems to enable access to improved energy efficiency. Long lifetime demonstrated under this program will translate to longer-life LED products which will provide increased value to the consumer and extended energy efficiency for the general public
- Program led to commercialization of coating solution that will be manufactured in the US and will generate jobs
- Technical learning’s from the program has enable WhiteOptics to gain a competency in optical coatings that will lead to development of additional products for the LED industry.

This will result in additional jobs and products that enable overall energy and cost savings with LED products.

B. Accomplishments vs Objectives

The program met all milestones defined for BP 1 thru 3. Key milestones achieved included demonstrating a coating reflectance of 97% along with a cost effective process to apply the coating on light fixture surface material. Reflective composite layer was successfully applied using a large scale metal coating process. A cost effective coating process on 3D discrete parts was also demonstrated which met the less-than \$0.80/sqft Bill of Material milestone. Extensive accelerated durability testing was performed for the various prototypes. The program completed within budget and WhiteOptics has leveraged learning's from the program to commercialize new products.

Below is a detailed summary of the accomplishments compared with the original objectives of the project:

Milestone	Description	Metric	Accomplishments
PH I: Milestone 1	Relationship between particle size distribution and dispersion rheology established	<u>Optical Performance:</u> - Reflectance (R550): - Chromaticity: x,y <u>Dispersion:</u> - Particle size - dispersion viscosity	- 97% reflectance @R550 - dX, dY <10% from starting fiber - Particle size reduction <50 microns demonstrated - Low viscosity solution
PH I: Milestone 2	Optimal dispersion system and processing conditions identified	<u>Resin system</u> - cure time - materials (BOM) cost/sqft	- No particle settling within 1 month - Cure time <1min - BOM (materials only) <\$0.30/sqft
PH I: Milestone 3	Coating process selected and demonstrated	<u>Coating method</u> -roll/knife-coat/slot-die <u>Coating uniformity:</u> -Surface roughness (Ra) <u>Manufacturability/ Cost:</u> - cost/sqft estimate based on process/conditions	- Roll coating selected - Ra <20 microns - <\$0.30/sqft process cost
PH I: Milestone 4	Uniform coated layer with greater than 97% reflectance and favorable mechanical	<u>Coating Performance:</u> - Surface uniformity <u>Mechanical</u> - ASTM D522, 0-T bend adhesion test	- Thickness variation across web +/-10% - no blistering, gels, cracks - No adhesion failure with 0-T test and ball impact test

	characteristics demonstrated	- ASTM D2774-84, impact adhesion test	
PH I: Milestone 5	Accelerated durability testing protocol and accepted control material defined	<u>Lifetime/Durability:</u> - Spectral response vs time (accelerated): - Relative luminaire LM70 (vs reference):	- Test method defined - Reference luminaire defined
PH II: Milestone 1	Cost effectiveness of coating process on light fixture surface material demonstrated on large scale process	<u>Optical Performance:</u> - Reflectance (R550): - Chromaticity: - Diffuse (%gloss @60deg): - Uniformity (stdev basis weight): <u>Manufacturability/ Cost:</u> - Cure time - BOM cost/sqft <u>Efficacy in Luminaire:</u> - Lumens/watt in reference fixture	- R550 > 97% - Batch variations for optical /mechanical +-5% - >10% efficacy improvement in reference luminaire - Total BOM <\$0.80/sqft
PH II: Milestone 2	Durability of composite material vs control demonstrated in accelerated testing	<u>Lifetime/Durability:</u> - Spectral response vs time (accelerated): - Relative luminaire LM70 (vs reference):	- Lab coating samples with <2% dE over 2000 hours exposure demonstrated - Luminaire lumens/watt depreciation <5% vs reference
PH II: Milestone 3	Alternative molded composite reflectors demonstrated	<u>Optical Performance:</u> - Reflectance (R550): <u>Mechanical:</u> - Part stiffness/strength - Dimensional accuracy <u>Manufacturability/ Cost:</u> - mold cycle time - processing/part	- R550 96% for production parts - Spray-coated discrete parts with mechanical stability (FRP 5VA plastic) demonstrated - cycle time < 0.5 min

C. Project Activities Summary

Summarize project activities for the entire period of funding, including original hypotheses, approaches used, problems encountered and departure from planned methodology, and an assessment of their impact on the project results. Include, if applicable, facts, figures, analyses, and assumptions used during the life of the project to support the conclusions.

Budget Period 1

Task 1: Characterizing Microfiber Substrate

- Multiple flash spun HDPE and microporous PET substrates were tested
- Reflectance was measured for increasing thickness and density using X-Rite SP62 spectrophotometer
- R550 reflectance average of 20 measurements across sheet showed that the base fiber substrate provided a potential for >98% reflectance

Task 2: Create and characterize fiber size distributions

The following milling techniques were attempted: Rotor milling, Co-mill, Hammer mill, Attrition mill, Cryo ball mill.

- *Mercury Porisimetry was used to measure pore size distribution between 100 and 1000 nanometers*
- *Was able to affect pore size distribution via particle size reduction method*
- *Was able to correlate pore volume to reflectance for given particle density*

A screening technique that measured particle size reduction method effectiveness was developed.

Task 3.1: Select resin/binder system

Resin/binder material was screened based on the following criteria:

- Fast cure @ <120C
- REACH/RoHS compliant
- Optically neutral
- Relative low cost
- Compatible with fiber particle

Results:

- Evaluated thermal curable acrylates, epoxy, epoxy/acrylate hybrid, PUD binder systems
- Evaluated variety of catalysts, dispersants, additives, and cross linkers
- Measurable Variables (Y's):
Reflectance, Cure Time, Viscosity, Coating uniformity, Gloss, Bend Test, Adhesion
- Selected PUD based on mechanical/curing/optical/reflectance/dispersion/process
- Preliminary testing results on coating equipment confirmed curing speed/process ability acceptable

Task 4.0 Optical and performance testing of coatings

Coating with optimal particle dispersion was measured at various thicknesses. 97% reflectance was achieved.

Figure: Coating Reflectance at Increasing Thickness

Coatings were applied inside the optical mixing chamber of a Cree CR6 commercial 60watt replacement LED downlight fixture with existing reflector optics removed. The coatings demonstrated increased light output over the existing white paint finish. Improvement was exponential (97% reflectance gave a 3% output increase over 96% reflectance).

Figure: Relative Light Output vs Coating Reflectance

Finally, the reflector finishes had no effect on color or color rendering index (CRI).

Figure: Effect of Reflector on Color

Task 5.0 Short Term Thermal testing of dispersions

TGA and DSC analysis of the various coating formulations showed that the polymeric reactions were fully reacted at time of cure.

Figure: TGA and DSC Analysis of Coating Formulations

Budget Periods 2 & 3

Accelerated Durability Testing

University of Delaware let the effort to perform accelerated durability testing on the various candidates generated throughout the program. Over 100 samples were tested over a period of 18 months. Most samples were tested for 1000 to 2000 hours and were subjected to UV exposure, thermal stability, freeze-thaw cycling, and humidity/water immersion tests.

Accelerated UV Testing

- Exposed coating candidates to 313nm ultraviolet radiation at 60C
- Monitored reflectance, surface roughness, adhesion
- Demonstrated coatings with stable properties in over 1500 hours in accelerated testing

Thermal Aging

- Samples aged per ASTM Standard D-6944 Resistance of Cured Coatings to Thermal Cycling
- Chemical changes are monitored using FTIR
- Physical changes are monitored using SEM and SWLI

Figure: Effect of Freeze/Thaw Cycle on Reflectance

Figure: Effect of Water Immersion on Reflectance

Manufacturing Demonstration

- Coating solution dispersion scaled-up to drum quantities for full scale coating system
- Coating to film carrier demonstrated
- 5 full-scale coating trials performed
- Significant learning's on:
 - Solution pot-time, transport, stability
 - Film forming dynamics in high airflow systems
 - Achievable line speed
 - Batch-to-batch reproducibility
- Developed spray coating for 3 dimensional reflector designs

D. Products Developed

a. Publications:

- Presentation presented at DOE SSL R&D Workshop 2011
- Poster presented at DOE SSL R&D Workshop 2011
- Poster at DOE SSL R&D Workshop 2012
- Poster at DOE SSL R&D Workshop 2013
- International Journal of Adhesion & Adhesives

"Adhesion Study of High Reflectivity of Water-based Coatings"

S. Bhargava, R. D. Lewis, M. Kubota, X. Li, S. G. Advani, J. M. Deitzel, A. K. Prasad

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- June 1st, 2011
 UDEL Poster: Composite Films for Reflection Application
 M. Kubota, S. Bhargava, R. D. Lewis, X. Li, S. G. Advani, A. K. Prasad, J. M. Deitzel
 - May 9th 2012
 UDEL Poster: High Reflectance Coatings with Superior Adhesion Properties
 S. Bhargava, R. D. Lewis, M. Kubota, X. Li, S. G. Advani, J. M. Deitzel, A. K. Prasad
 - July 3rd 2013
 UDEL Poster: Optical Coating Aging and Performance Degradation
 M. Kubota, S. Bhargava, R. D. Lewis, S. G. Advani, A. K. Prasad, J. M. Deitzel
- b. Web site or other Internet sites that reflect the results of this project:
- None at this time
- c. Networks or collaborations fostered:
- As a result of this project, WhiteOptics continues to contract UDEL for collaborative research.
- d. Technologies/Techniques:
- WhiteOptics has developed techniques for designing and scaling up optical coatings.
- e. Inventions/Patent Applications, licensing agreements;
- No patents were filed under this program.
- f. Other products, such as data or databases, physical collections, audio or video, software or netware, models, educational aid or curricula, instruments or equipment.
- Not applicable