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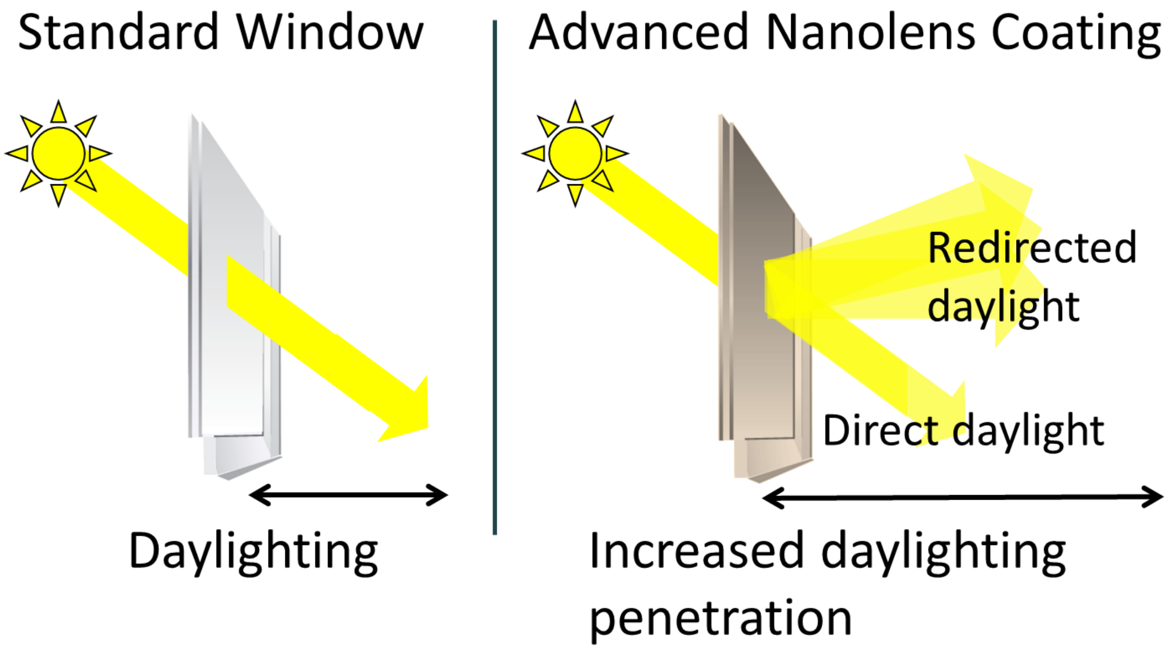
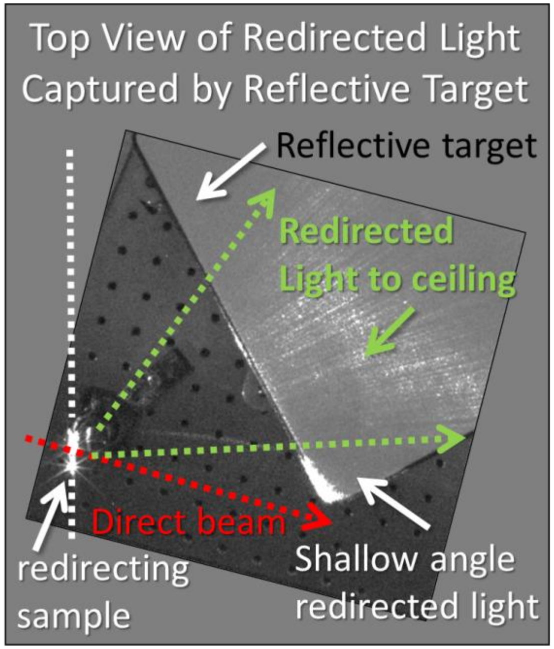
To develop a novel, low-cost window coating to double daylight penetration to offset lighting energy use



Demonstration of the effect



Nanolens Window Coatings for Daylighting

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Purpose & Objectives

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Problem Statement: PNNL is developing a novel, low-cost window coating to redirect daylight deeper into buildings to significantly offset lighting energy.

Impact of Project: A successful daylighting coating with high market penetration has potential for 0.4 Quad/yr lighting energy savings with an associated CO_2 offset of 7 Mtons/yr at \$2-3/ft^2.

Project Focus: The development of the daylighting coatings aligns with BTO goals by focusing on bringing to market a novel emerging technology with potential for savings of approximately 50% of lighting energy in commercial buildings*.

*Arasteh, D.S., Steve; Apte, Josh; LaFrance, Marc, *Zero Energy Windows.* Proceedings of the 2006 ACEEE Summer Study on Energy Efficiency in Buildings, 2006.

Approach

Approach: The goal is to demonstrate a low-cost, scalable, high performance light-redirecting coating. PNNL employs a synergistic fabrication, modeling, and characterization approach for rapid progress.

Key Issues:

- High coating performance for light redirection (30-60% light redirection)
- Broad wavelength coating response
- Scalability and cost

Distinctive Characteristics:

- Unique window coating instead of mirrors or light shelves
- Novel sub-wavelength coating features

Approach – Current SOA Daylighting

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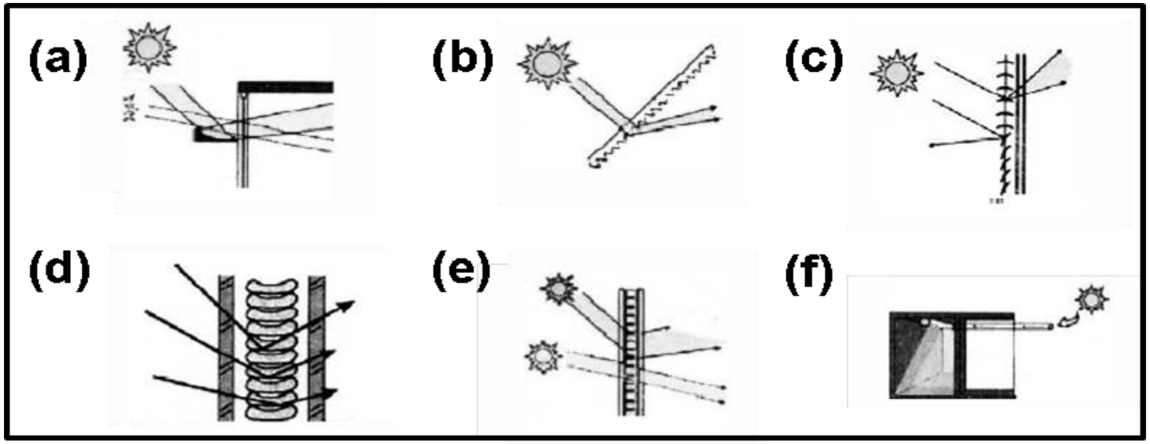
- Current daylighting technologies are expensive/ bulky/ non viewable
- Not widely adopted
- Energy savings not realized
- Need low-cost films like Low-E to improve market impact
- PNNL Nanolens coating addresses these issues

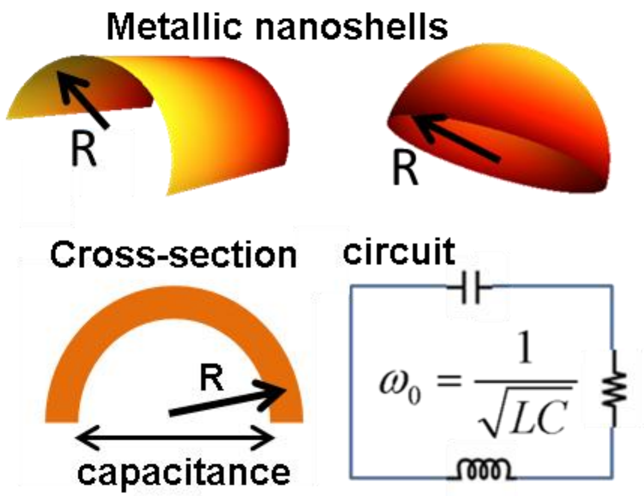


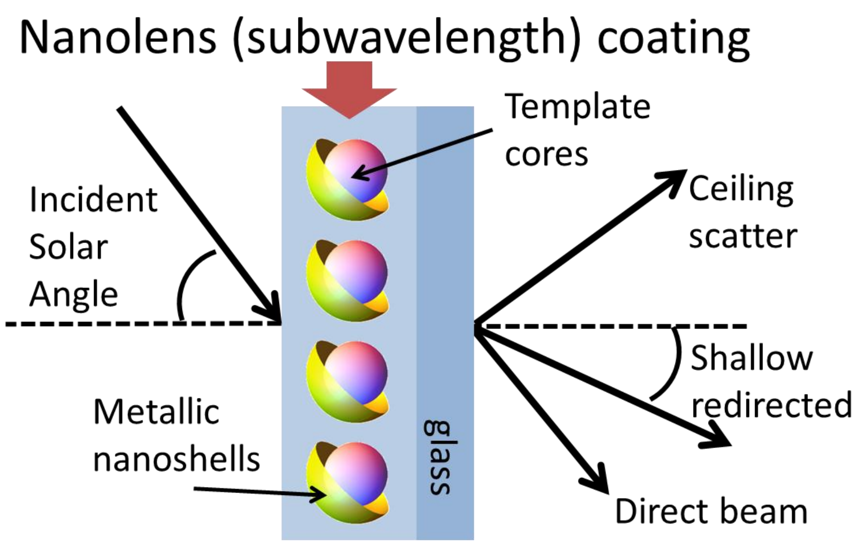
Kischkoweit-Lopin, M., *An overview of daylighting systems.* Solar Energy, 2002. **73**: 77.

	Technology	View (Y/N)	Maintenance	form	cost	comments
	Proposed – meta-material coatings	Y	None in double pane	Thin-film glass coating	\$3/ft^2	Novel approach/potential for thermal management
(a)	Light Shelves	N	High	Large architectural component	\$100/shelf	available – specific design per window
(b)	Prismatic Panels	N	Alone - High None if in double pane	Sheet or thick plastic panel	\$19/ft^2	
(c)	Louvers/Mirrored Blinds	Y- partially obstructed	High	Blinds	\$35/ft^2	available
(d)	Sun directing glass	N	None if in double pane	Thick plastic panel	\$19/ft^2	
(e)	Laser-cut panels	Y- partially obstructed	None	Monolithic glass	\$9-12/ft^2	Fragility issues
(f)	Light pipes	N	None	Bulky tubes/fibers	High cost	Specific design per space and high installation costs
	Glass block	N	None	Thick glass wall	\$16/ft^2	High installation cost

Subwavelength Structures:

- Basic unit for redirecting coating is an oriented anisotropic metal nanoshell – light redirection based on structure orientation
- Based on Open Ring Resonator (ORR) metamaterial design and work by Halas group*
- Coating consists of close-packed array of single orientation nanoshells
- Multiple shapes possible – hemisphere, half-cylinder, others.

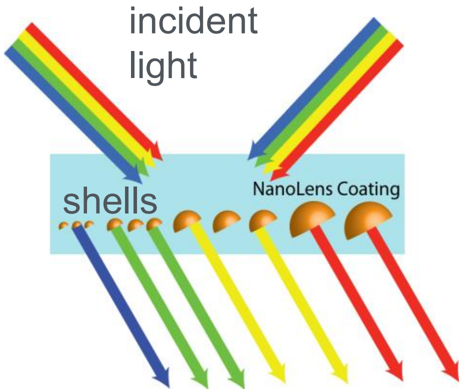




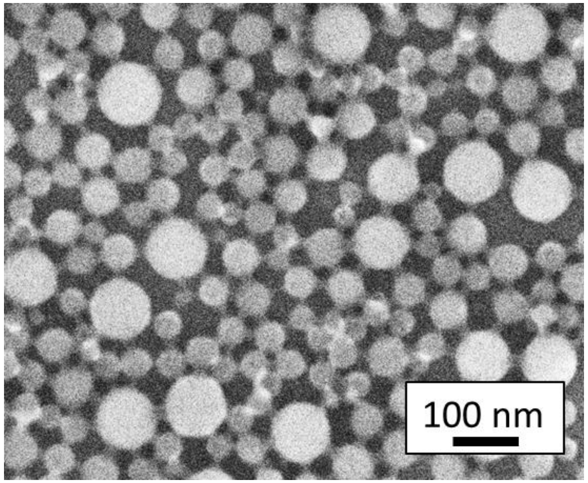
Mirin, *et al.*, *Light-bending nanoparticles.* Nano Letters (2009) 1255.

Resonance Effects:

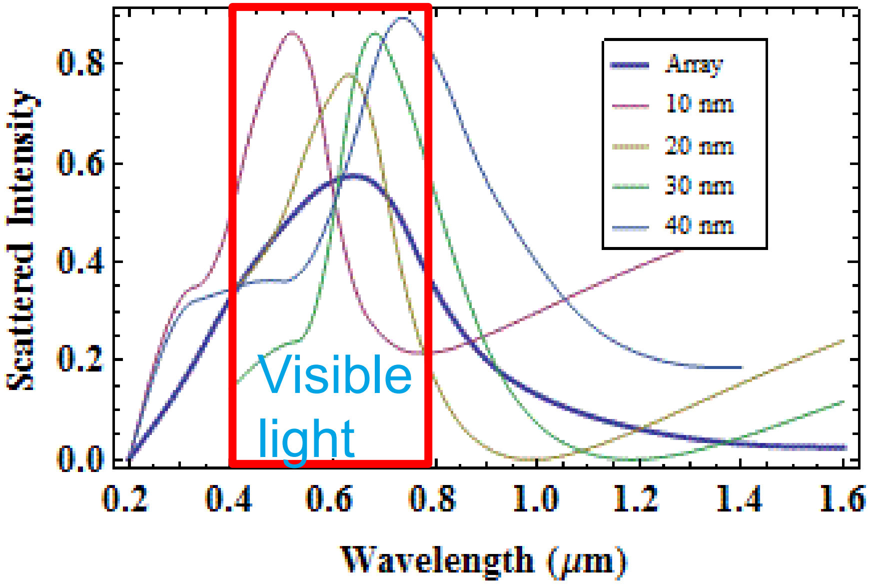
- ORR structures have a size dependent resonance
- Solution is to fabricate multi-size array via template
- IR response is also possible



Multi-sized spherical template



Scattering Response



Approach – Coating Fabrication and Scalability

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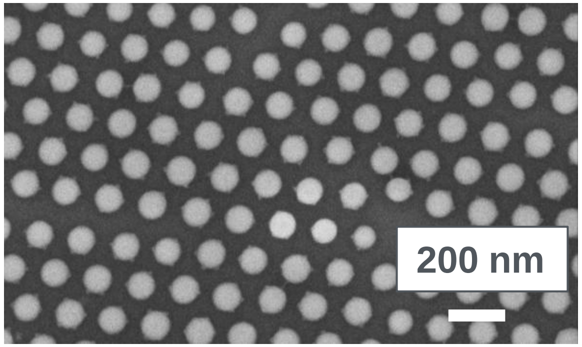
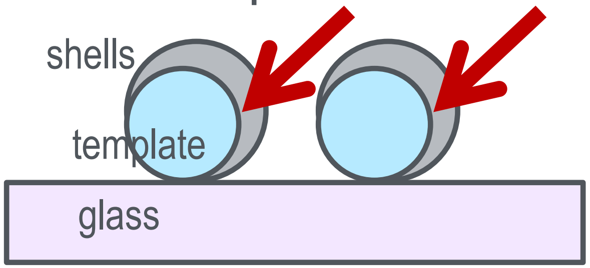
Fabrication and Scalability

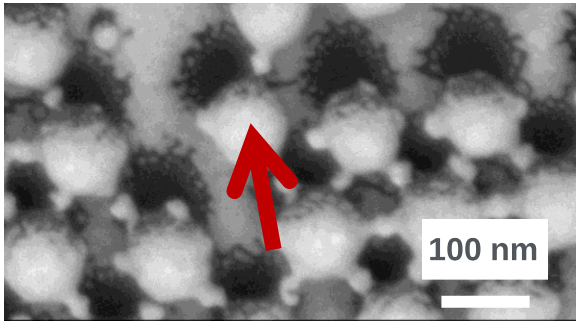
- Metallic shells fabricated via sputter deposition on nanoscale templates
- Current lab-scale – 2-3” samples
- PNNL has considered several potential routes to large scale template and metal coatings
- Discussions with industry to determine path forward

Template deposition



Metal deposition

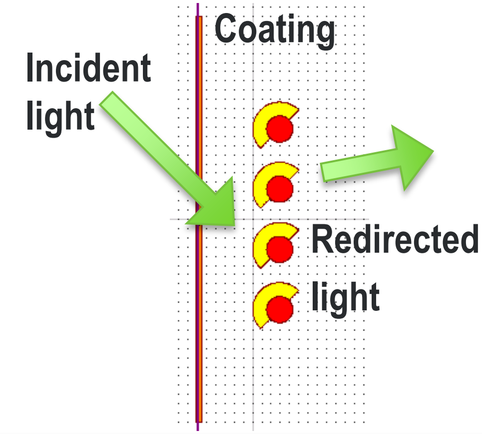




Approach – Modeling & Optical Measurements

Modeling:

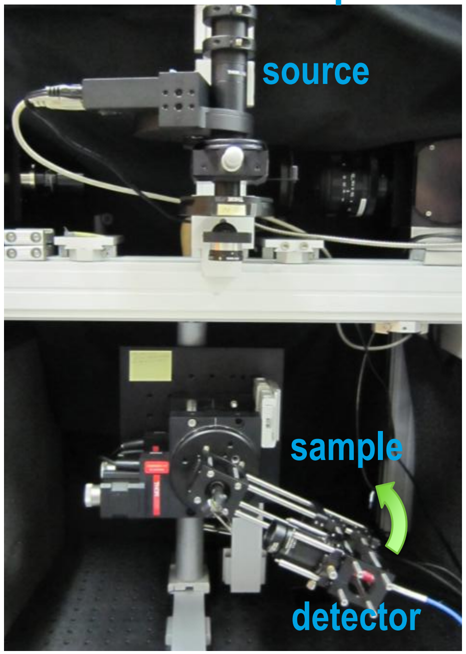
- FDTD numerical modeling gives near field transmission & far-field light redirection
- Allows rapid evaluation of fabrication parameters
  - Thickness, size, orientation, metal, wavelength, angle of incidence



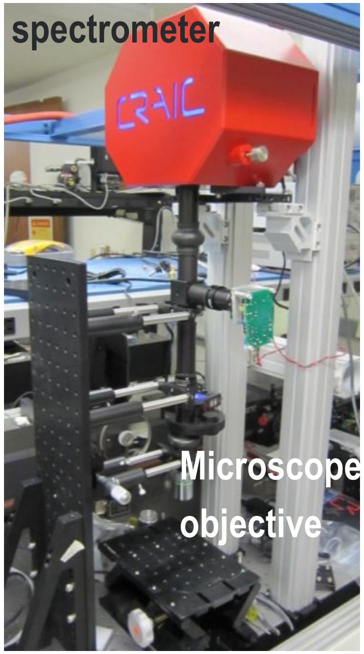
Measurements:

- Performance is evaluated vs. baseline flat coatings
- Coatings are evaluated as a function of:
  - Wavelength
  - Incident angle
  - Polarization
- Microspectrophotometer used for rapid testing and defect analysis

Measurement setup



Microspectrophotometer



Accomplishments and Progress

Accomplishments: PNNL has demonstrated proof-of-concept light redirection and broad wavelength response from the sub-wavelength coatings for daylighting. PNNL is currently working on improved performance.

Progress on Goals: PNNL's progress is well aligned with the project goals & path to commercialization:

A – Demonstrate proof-of-concept (FY12)

B – Demonstrate improved performance (FY13)

C – Demonstrate low-cost scale-up feasibility/durability (FY14,15)

Awards/Recognition: This work has been reported on at NFRC and DOE workshops. Provisional patents have been filed and a publication has been submitted.

Accomplishments and Progress

- Proof-of-concept: single wavelength light redirection from sub-wavelength structure

Schematic and SEM of sub-wavelength structure

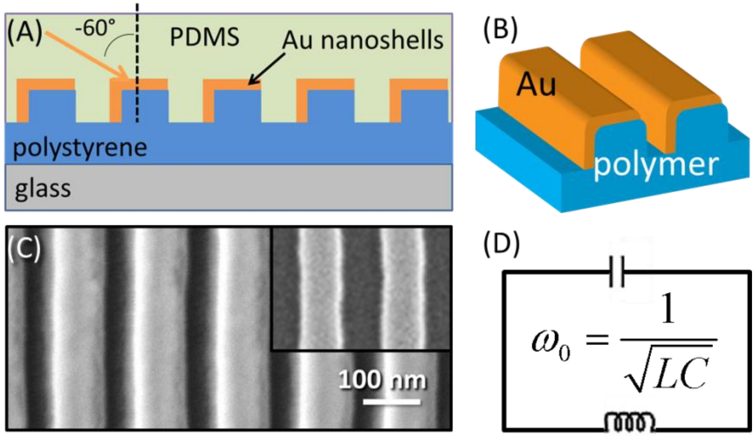
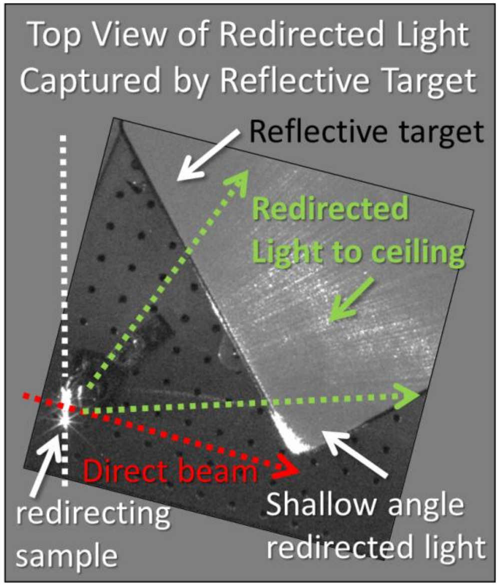
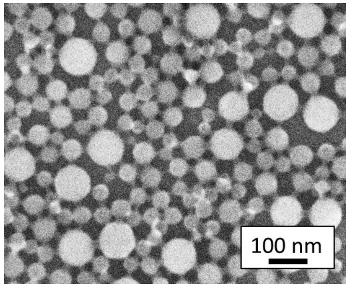


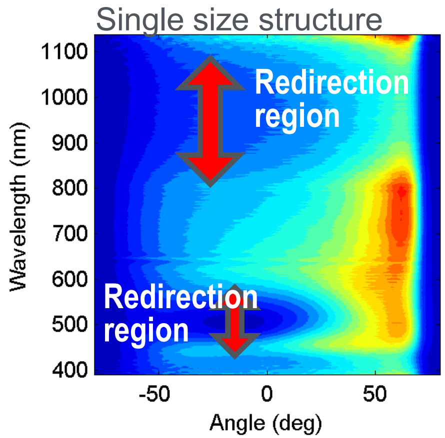
Photo of effect

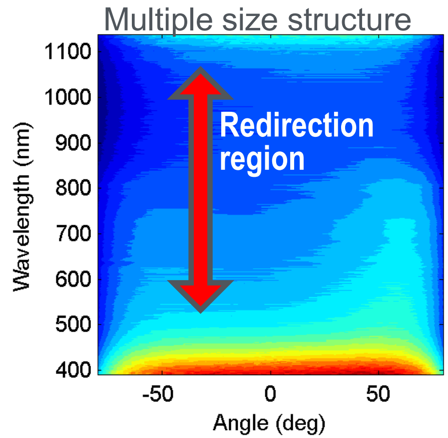


- Proof-of-concept: Broad wavelength response



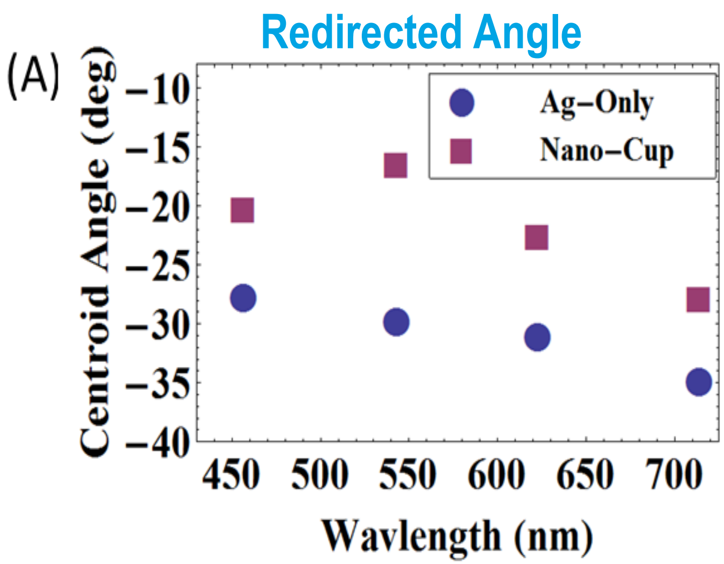
Multiple size template

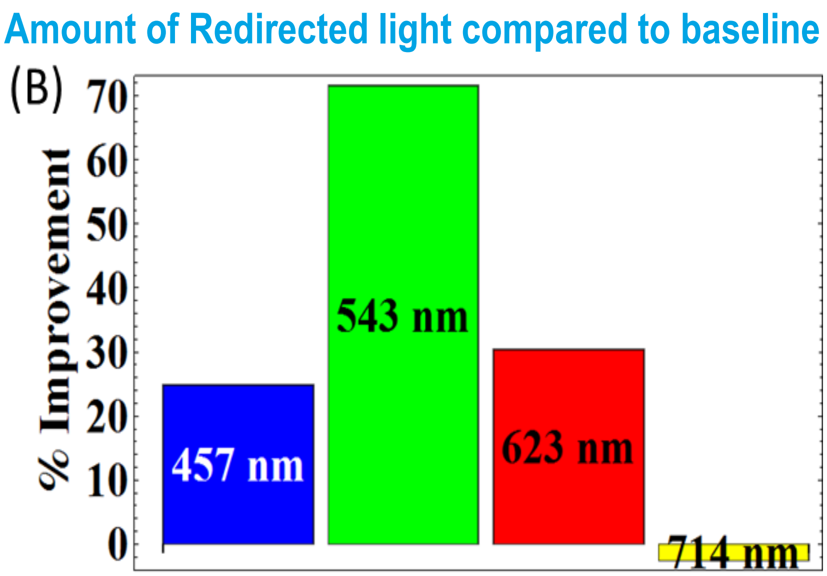




Accomplishments and Progress – Modeling

- Modeling shows that light is redirected to shallower angles
- Up to 70% light redirection for a single wavelength structure





Note: this is for a single wavelength structure. Full visible spectrum response improvement is possible with multiple size structures

Accomplishments and Progress - Path Forward

Performance

- PNNL has made significant progress to date on the R&D challenges
- The path forward to improving coating performance is:
  - Significantly reduce film defects
  - Improve metal shell conductivity
  - Increase shell packing density, option for multiple layers
  - Optimize design parameters (tilt, thickness, metal choice)
- Color mixing and view have been considered with no show-stoppers

Scale-up & Cost

- PNNL has identified potential manufacturing processes and routes to scale up
- PNNL has also done preliminary cost analysis
- In process of establishing CRADA with PPG Industries
- Future work will focus on these aspects

Project Plan & Schedule

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Project start date: October 2010
Project planned completion date: September 2015
FY12 Milestones – completed
FY13 Milestones – in progress
- Modeling guide on Fabrication parameter for optimal performance end Q3
- 10% light redirection over 30% of visible range - end Q4
- Report on scalability – end Q4

Summary	
Agreement Number: 18835-18100 WBS: 01	
Project Number: 60339	
B&R Code-fund Value Program Code BT0304030 05450-1004219	

Legend	
	Work completed
	Active Task
	Milestones & Deliverables (Original Plan)
	Milestones & Deliverables (Actual)

	FY2012				FY2013				FY2014			
Task / Event	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Octt-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Project Name: Advanced Nanolens Coatings for Daylighting												
Task: Test Nanolens Coatings Fabrication & Measurement												
Task: Modeling of Nanolens Coating performance												
Q3 Milestone: PNNL demonstrates modeling 10% redirection, single wavelength												
Q3 Milestone: PNNL provides R&D roadmap for Nanolens Coatings												
Current work and future research												
Modeling to determine optimal performance coatings (report on key parameters)												
Fabrication of Improved Nanolens coatings with higher performance (10% experimental)												
Path to Commercilization (Report on path to scale up)												

Project Budget

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Project Budget: Project start FY11 (Scoping study, $100K), FY12 (technical feasibility, $100K), FY13 (Enhance Performance, $250K)

Variances: No variances to date

Cost to Date: FY11- $100K, FY12 - $100K, FY13 - $90K to date

Additional Funding: Working on establishing CRADA in FY13 with PPG industries.

Budget History					
FY2011		FY2012		FY2013	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$100K	$0K	$100K	$0K	$250K	$0K

Project Integration, Collaboration & Market Impact

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Partners, Subcontractors, and Collaborators: PNNL has been consulting with PPG industries about the technology and is in discussions for a CRADA on future work.

Technology Transfer, Deployment, Market Impact: PNNL will address the lab-scale R&D challenges and partner with industry to address cost, scale-up, and other factors. The successful technology will be licensed to an appropriate manufacturer.

Communications:

- Nanolens Scoping Study Report (DOE, 2011) – identify potential market impact
- Nanolens R&D roadmap Report (DOE, 2012) – outline R&D path to market
- NFRC Presentation (Dr. Phelan, 2012)
- DOE Windows Roadmap Workshop Presentation (Dr. Gaspar, 2012)
- Journal Article Submitted (Dr. Alvine, 2013) – technological results

Next Steps and Future Plans

Next Steps and Future Plans:

- Improve broad-band light redirection performance to 10% (FY13), then to 30-60% (FY14)
- Establish CRADA with PPG industries (FY13)
- Intermediate scale-up demonstration (FY14)
- Durability testing for lifetime assessment (FY15)
- Refine materials/process selection based on cost analysis (FY15)