

1. Systems Vision and Value Added of the Center

1.1 Systems Vision

Light plays a fundamental and growing role in our surroundings, impacting energy efficiency, productivity, health, information, environmental sustainability, and economic prosperity. The rapid development of solid-state (LED, or Light Emitting Diode) light bulbs is promising to deliver a new era of energy efficient, reliable lighting, but these LED bulbs and lamps are only a first step. The Smart Lighting Engineering Research Center (ERC) will develop transformational lighting systems which utilize the full gamut of technical capabilities offered by LED lighting augmented by advanced light sensors and integrated lighting control systems. The goal of the Smart Lighting Engineering Research Center is to launch a new era in solid state lighting systems that generate, control, and adapt light to improve the human condition in ways never before possible, and in the process, create a dynamic, global and entrepreneurial center for driving *lighting innovation for a smarter tomorrow*.

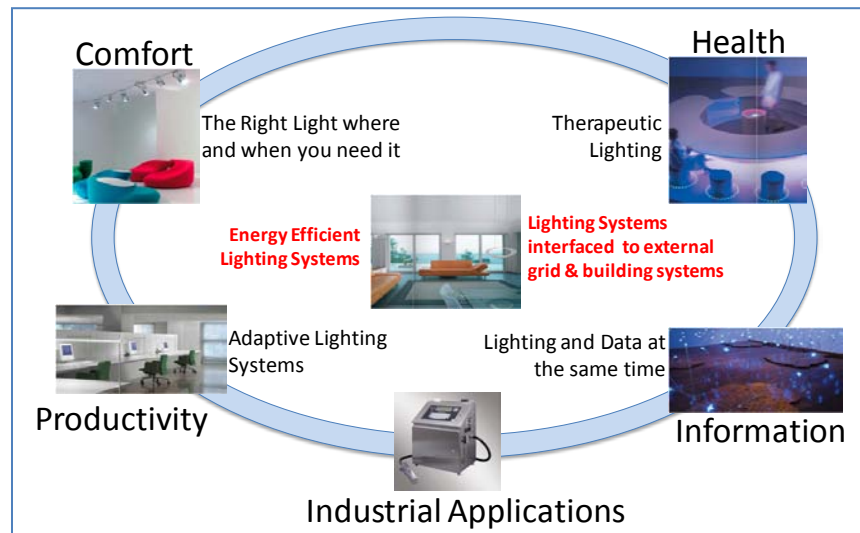


Figure (1). Broad impacts of future smart lighting systems

As shown in Figure (1), lighting systems of the future will have a broad role in how humans experience their environments. They will be able to automatically control light intensity and color to match daylight, harvest and utilize lighting information related to occupancy, motion, health and safety, convey information for enhanced communication, understand and influence human physiological response for improved comfort and productivity, and enable bio-detection in medical, homeland security, agricultural and food packaging applications.

One key vision from Figure (1) is the role Smart Lighting will play in enhancing human health, comfort and productivity with new approaches to energy efficient lighting systems for both illumination and display technology. The impact of lighting on human factors is continuing to evolve. While much is known about how humans process visual information, lighting impacts on circadian human factors and the relationship of those factors to human health and well being are only now beginning to emerge. One of the exciting challenges for smart lighting in the next

decade will be to integrate what is already known about the human visual system (but not reflected in current lighting standards) with the science that is emerging about the human circadian system response to light. The Smart Lighting ERC, in collaboration with the Lighting Research Center, will address the significant technical barriers to efficient color adjustable, ergonomically correct and cost effective lighting systems, providing both the physiological basis for new lighting design standards and the Smart Lighting Systems needed to meet those standards. In addition addressing standards for human factors considerations in new lighting systems, tough, new standards for improved energy efficiency in display technologies will also benefit from improved lighting sources using polarized and efficient RGB backlighting systems currently under development in the ERC.

A second key vision from Figure (1) is the role of Smart Lighting in providing data communications. Modulated solid state lighting is fundamentally much better suited than radio to achieving very high data rate densities (Mb/s/m^2) that will be required to satisfy the very rapidly growing demand for high speed data that quickly overwhelms scarce radio spectrum resources, resulting in severe localized congestion, or “wireless gridlock.” In contrast, visible light can be directed and sequestered, enabling multiple independent high capacity links to occupy nearby spaces, thus supporting much larger density of data traffic. This effort will produce high data rate individual links to directly compete with existing and emerging RF technologies such as WiFi in terms of the *aggregate* data rates for indoor settings such as rooms, halls, and airplane cabins in which every luminaire becomes a cell, with lighting as a byproduct.

A third key vision from Figure (1) is that Smart Lighting can lead the way to devise an entirely new class of biological sensing devices that are simply not possible with conventional lighting systems. Low cost biohazard and medical testing sensors require the development of both solid state lighting sources and very sensitive detection systems that can be used to signal the presence of harmful agents (chemical or biological) with high accuracy and fast response times. This segment of research is strongly aligned with healthy room lighting and lighting communications in that these technologies are enabled by many of the core materials, device and system level technologies already under development in the Smart Lighting ERC, where the potential of using light to improve the human condition in ways never before possible is explored.

Modern lighting technologies are evolving very rapidly with dramatic impacts on global markets and related industrial sectors. The transition from incandescent and fluorescent lamp fixtures to LED source technologies may be viewed as the “First Wave” of lighting system innovation. In this First Wave, new generations of LED sources are simply plugged into traditional light sockets. However, the role of illumination is not fundamentally changed and the human interaction with the lighting system is still limited to “on”, “off”, and “dim”. In the “Second Wave” of lighting system innovation, “smart lighting” systems will be created through the integration of internal and external sensors and the introduction of enabling technologies providing control and communications of the integrated systems. Currently, the functionality of such “smart” systems is limited by fundamental barriers in the availability of (a) efficient, controllable and adaptive light sources, (b) versatile and inexpensive light sensors, and (c) integrative systems algorithms for control, communications, and networking of these components. The goal of the Smart Lighting ERC is to overcome these barriers through basic

research and to collaborate with industrial partners to create new products and industries based on these principles in each of the three key areas (lighting, communications, and biosensing).

The overall vision for the Smart Lighting ERC has evolved and matured over the last two years. The broadened systems vision of smart sensor-based lighting systems and the wide range of applications that are enabled are reflected in the Year 3 strategic plan by incorporating three fundamental changes:

1. The new plan expands the scope of fundamental science and device technologies to include the *Sensor Thrust*, supporting sensor design and integration. In addition, the *Systems Thrust* is expanded to explicitly support control and communications challenges of source-sensor integration.
2. The new plan increases the role of the *Testbed Thrust*. Each Testbed Project is a vertical integration program with broad interdisciplinary participation across the center. Each Testbed provides a proof-of-concept platform for integrated systems experiments, demonstration, and evaluation. These Testbeds are aligned with the three key visions outlined from Figure 1.
3. The new plan creates the *Translational Applications Thrust* to address the core goals of industrial participation and collaboration in our Gen-3 ERC model. At the thrust level, the translation activities will receive both broad interdisciplinary team participation, and also will benefit from unifying facilities, processes, and management needed to make these transitions successful.

The revised plan for Year 3 is accompanied by changes in project personnel and programs from Year 2. Some projects have been dropped in order to make room for new priorities, or, where possible, are moved to a translation and commercialization phase. The revised plan builds on the core strengths of the ERC team and facilities and adds capabilities in areas that support the systems vision. These changes conform to inputs from the prior annual review (Year 1), as well as input from discussions that have occurred with the Industrial and Scientific Advisory Boards this year.

Today's global lighting market is over \$100B and is projected to reach \$132B in 2011. Almost 20% of all electrical energy worldwide is used for lighting. LEDs lighting currently constitutes only about 1% of the global market, and there are enormous market and revenue drivers underlying technological innovation in LED lighting. Rapid industrial progress in the "First Wave" of solid state lighting has doubled the efficacy of a white LED in the past two years. Strategically, the Smart Lighting ERC needs to complement and enhance the functionality of new generations of lighting systems (the Second Wave), and not compete with rapid industrial development of near-term commercial light source technologies. This strategic "smart systems" perspective will, leverage industry progress through collaborative participation of global industrial partners, and the continued growth of that participation is a high priority for the ERC.

1.2 Value Added and Broader Impacts

Research

Engineered Systems Level Approach and Advances: The Smart Lighting ERC research focuses on systems driven transformational research in the areas of energy efficient lighting, light based communications and health/biosensing. At the beginning of Year 2, the ERC restructured the programs in the Materials and Device Thrusts for better alignment to Test Bed requirements, and formed a Systems Integration Committee with industry participation (Philips). This improved the systems level focus but the ERC was still strongly materials and devices focused. To strengthen the systems level focus, the ERC has formulated a top down systems level vision of Smart Lighting attributes in each of the core applications of the ERC. In a series of meetings of all ERC investigators with the new Director in 2010, a new 3 Level diagram was formulated to enable clearer systems level focus. The historically strong materials and device capabilities and thrusts of the ERC were mapped into new sources and sensors thrusts and driven by clearly articulated barriers and systems requirements.

ERC testbed activities drive collaborative interactions across the ERC both internal and external to the ERC. Translational activities are emerging from the Smart Lighting Communications testbed as user friendly VLC evaluation kits have been made available to industries in order to explore this new technology and to define new applications and system level requirements. The Smart Spaces (lighting) testbed has engaged with Renaissance Lighting to explore the interaction of commercially available (but very inefficient) color tunable lighting systems and light sensors and support the development of new lighting control architectures and aspects of color science. Thus the test beds are driving the concurrent development of Smart Lighting systems level work by engaging industry participation at an early development stage while simultaneously providing design and performance requirements for new generations of more efficient LED sources, more sensitive sensors, and new, adaptive networking and control technologies.

Research Productivity: During Year 2, the Smart Lighting ERC demonstrated strong growth in research productivity. Through 4/30/10, there were 49 publications in peer reviewed journals, 41 peer reviewed conference proceedings and 12 invention disclosures based on ERC core research. Professor Hatice Altug's exciting work on the combination of nanoplasmonic sensors with nanofluidics for transformative LED-enabled biosensors was featured on the cover of the January 11, 2010 issue of Applied Physics Letters, further described in Highlights Section 1.3 of this report.

Educational Outcomes

Curriculum Impact: Since the start of the Smart Lighting ERC, three new topical courses for senior undergraduates and graduate students were developed, and Smart Lighting ERC content was introduced to another 11 previously existing courses.

New Courses:

- EK131/132 Photonics: Engineering the Light (BU)
- EC481: Fundamentals of Nanotechnology and Nanomaterials (BU)
- NSMS 550/ECE 550/ChNE 550: Societal and Ethical Issues in Nanotechnology (UNM)

Existing Courses Modified to Include Smart Lighting Topics

- ECSE 4900: ECSE Sr. Design Course (RPI)
- ECSE 6270: Optoelectronics/Physics of Photonics (RPI)
- ECSE 6610: Pattern Recognition (RPI)
- ECON 4140: Structure of Industry: Competition, ... (RPI)
- MGT 6630/4430: Starting up a new Venture (RPI)
- MGT 6620: Principles of Technological Entrepreneurship (RPI)
- ECSE 4964: Optoelectronics Technology
- Summer Challenge: Engineering with Smart Light (BU)
- Introduction to Engineering: Smart Lighting 2010 (BU)
- Nanostructured Materials (RPI)
- NSMS 650: Research Problems in Smart Lighting (UNM)

Pre-college Impact: In Year 2, ERC educational outreach to K-12 teachers was significantly expanded with three programs reaching dozens of middle school and high school teachers. These training programs utilized the well-known Mobile Studio Platform (Highlights Section 1.3.7) applied to LED lighting and visible light communications.

- In August 2009, and in conjunction with our Outreach University Partner, Rose Hulman, over 20 high school teachers participated in Mobile Studio training that included Smart Lighting topics.
- Workshops were held at RPI for 12 teachers and their principal from the Cleveland MC²STEM High School at GE's NELA Park and 4 teachers from the Academy of Engineering at Albany (NY) High School.
- In conjunction with the K-12 Education Program Manager and Director of Community Involvement Sandia National Laboratories (SNL), the Smart Lighting ERC will contribute a half day workshop on Smart Lighting that is part of a 1-week professional development event for Middle School teachers that has been organized by SNL

Over a dozen outreach efforts presenting Smart Lighting concepts were conducted during Year 2, reaching hundreds of students in grades K through 12. Some of these programs have been performed in conjunction with the diversity pipeline programs Design Your Future Day and Exploring Engineering Day.

Industrial Collaboration and Technology Transfer Interactions

The ERC added six (6) new industrial members during Year 2, each contributing a member to the newly formed ERC Industrial Advisory Board (IAB). In September 2009, Dr. Silvia Mioc was hired as the Director of Industrial Collaboration. In Year 2, the IAB has convened monthly to review new developments, provide feedback on ERC activities, and suggest new directions and improvements to the operation of the ERC, including the formulation of the new ERC 3 Level Plan. The ERC submitted four NSF SECO SBIR proposals (two Phase II and two Phase I). This process drove new ERC/industry interactions in the areas of advanced materials, nanostructure fabrication technology, Smart Street Lighting development, and LED based light treatment systems for circadian rhythm issues management. The ERC recently learned that one of these proposals will be funded.

The Smart Lighting ERC held the first annual Industry-Academia Meeting at Boston University in early February, 2010. 49 attendees from outside the ERC, representing 25 companies, 4 Venture Capital firms, another ERC and 2 government funded R&D organizations) participated. They heard Smart Lighting ERC presentations and attended ERC student-lead poster sessions. Based on this meeting, the ERC is in active discussions with over 30 potential new industrial members.

During Year 2, the ERC has engaged LED companies in Asia to broaden its global reach. Interactions with Epistar and Genesis Photonics (both in Taiwan) have enabled the procurement of both standard and non-standard unpackaged LED chips to accelerate the development of VLC applications (Epistar/Professors Joyner and Little) and improved nanoparticle detectors for biosensors (Genesis Photonics/Professor Unlu). Industrial participation is also critical in early translational project work, where all three test beds (Lighting, Communications and Health/Biosensing) are deriving benefit from early industry participation and feedback on evolving Smart Lighting systems level developments.

Team and Its Diversity

Interdisciplinary Make-up: The ERC team consists of investigators from a broad array of disciplines: electrical, mechanical and chemical engineering, optical systems design, applied physics, materials science, architecture, biology, biophysics, and medicine as well as faculty in management and economics. The distribution of these participants by discipline is provided in Figure 2a.

Underrepresented groups: In year 2, the ERC expanded leadership, faculty and student involvement of underrepresented groups. Underrepresented faculty involvement increased from 5 in Year 1 to 9 in Year 2: Schadler, Sanderson, Altug, Figueiro, Hella, Joyner and Sawyer, Huang and Parsa. Underrepresented leadership involvement increased from 2 in Year 1 to 3 in Year 2: Washington, Veros, Mioc. Underrepresented research involvement now includes one thrust leader and three project leaders: Mona Hella (thrust leader), Figueiro, Hella and Sanderson (project leaders). REU participants in year 1 and year 2 were more than 50% female. The ERC participated in an HBCU ECE Workshop 4-6 November 2009 where 10 ECE Department Heads met to discuss faculty recruitment and research.

ERC Web **Table 1** that follows provides information about the the quantifiable outputs of the Center and compares the first year with the second year through April 30, 2010.

Table 1: Quantifiable Outputs				
Outputs	Early Cumulative Total [1]	September 01, 2008 - April 30, 2009	May 01, 2009 - April 30, 2010	All Years
Publications That Result from Center Support				
In Peer-Reviewed Technical Journals	0	4	49	53
In Peer-Reviewed Conference Proceedings	0	2	41	43
In Trade Journals	0	0	0	0
With Multiple Authors:	0	6	77	83
Co-authored with ERC Students	0	5	59	64
Co-authored with Industry	0	1	12	13
With Authors from Multiple Engineering Disciplines	0	0	29	29
With Authors from Both Engineering and non-Engineering Fields	0	0	28	28
with authors from multiple institutions	0	1	27	28
Publications That Result from Associated Projects in the Strategic Plan				
In Peer-Reviewed Technical Journals	0	0	22	22
In Peer-Reviewed Conference Proceedings	0	0	24	24
Publications Resulting From Sponsored Projects				
In Peer Reviewed Technical Journals	N/A	0	0	0
In Peer Reviewed Conference Proceedings	N/A	0	0	0
Participating Industrial and Practitioner Organizations				
Members	0	1	6	7 [2]
Affiliates	0	1	0	1 [2]
Contributing Organizations	0	1	2	3 [2]
ERC Technology Transfer				
Inventions Disclosed (submitted to agencies by researchers or technology transfer office)	0	0	18	18
Patent Applications Filed	0	0	12	12
Patents Awarded	0	0	2	2
Licenses Issued	0	0	0	0
Spin-off Companies Started	0	0	0	0
Estimated Number of Spin-off Company Employees	0	0	0	0
Building Codes Impacts	0	0	0	0
Technology Standards Impacts	0	0	0	0
New Surgical and other Medical Procedures Adopted	0	0	0	0
Degrees to ERC Students				
Bachelor's Degrees Granted	0	1	4	5
Master's Degrees Granted	0	3	5	8
Doctoral Degrees Granted	0	0	2	2
ERC Graduates Hired by				
Industry:	0	3	3	6
ERC Member Firms	0	0	1	1
Other U.S. Firms	0	3	1	4
Other Foreign Firms	0	0	1	1
Government	0	0	0	0
Academic Institutions	0	0	7	7
Other	0	0	0	0
Undecided/Still Looking/Unknown	0	0	0	0

ERC Influence on Curriculum				
New courses based on ERC research that have been approved by the curriculum committee and are currently offered [4]	0	2	3	5
Currently offered, on-going courses with ERC content	0	4	11	15
New Textbook Chapter Based on ERC Research	0	0	0	0
New Textbooks Based on ERC Research	0	0	0	0
Free-Standing Course Modules or Instructional CDs	0	0	3	3
New full degree programs based on ERC research	0	0	0	0
New degree minors or minor emphases based on ERC research	0	0	0	0
New certificate programs based on ERC research	0	0	0	0
Active Information Dissemination/Educational Outreach				
Workshops, Short Courses, and Webinars [3]	0	1	2	3
Number of participants that attended activity	N/A	2	270	272
Seminars, Colloquia, Invited Talks, etc.	0	7	9	16
ERC Sponsored Educational Outreach Events for K-12 students	0	3	12	15
Number of students that attended activity	0	86	364	450
Number of teachers that attended activity	0	4	23	27
ERC Sponsored Educational Outreach Events for Community College or Undergraduate students	0	0	5	5
Number of students that attended activity	0	0	99	99
Number of faculty that attended activity	0	0	8	8
Personnel Exchanges				
Student Internships in Industry	0	0	0	0
Faculty Working at Member Firm	0	0	0	0
Member Firm Personnel Working at ERC	0	0	0	0

[1] For Centers in operation for more than five years.

[2] Cumulative count of Individual Firms/Organizations may not equal the sum across all years.

[3] For years prior to 2009, the values include 'Workshops and short courses to industry' and 'Workshops and short courses to non-industry groups'

[4] New courses currently offered and approved by the curriculum committee are only counted in the first year that they are offered so there is no multiple counting of these courses.

Metric	Average All Active ERC's FY2009	Average Energy Sector FY2009	Average for Class of 2008 - FY 2009	Smart Lighting ERC at Rensselaer Polytechnic Institute Total	Smart Lighting ERC at Rensselaer Polytechnic Institute Total
	(20 ERC's)	(4 ERC's)	(5 ERC's)	FY2009	FY2010
Industrial Member Firms	18	21	9	1	6
Small	38%	52%	57%	100%	67%
Medium	14%	14%	4%	0%	0%
Large	48%	34%	39%	0%	33%
Non-Industry Sector Firms	1	1	0	0	0
Total Member Organizations	19	22	9	1	6
Affiliate Organizations	1	1	1	1	0
Contributing Organizations	1	1	1	1	2
Total Membership Fees Received	\$	\$	\$	\$	\$
Direct Sources of Support [1]	\$	\$	\$	\$	\$
NSF	67%	67%	72%	69%	49%
Industry	9%	8%	3%	1%	4%
Other Federal	0%	0%	0%	0%	0%
Academic	20%	16%	16%	20%	35%
State	2%	4%	4%	11%	11%
Other	2%	6%	6%	0%	0%
Associated Project Support	\$	\$	\$	\$	\$
ERC Personnel & Educational Participants[2] [3]	1,770	834	304	203	658
Leadership Team [7]	14	13	16	12	14
Faculty [2] [4]	43	37	39	35	49
Graduate Students [2]	73	77	64	38	45
Undergraduate Students [2]	26	27	16	30	36
REU Students	11	6	5	0	7
K-12 Teachers [3]	108	2	18	4	23
K-12 Students [3]	1,437	665	130	86	364
Faculty that attended ERC Sponsored Educational Outreach Events [3]	2	0	3	0	8
Community College or Undergraduate students that attended ERC Sponsored Educational Outreach Events [3]	26	0	11	0	99
% Women [5] [6]	60%	20%	22%	17%	22%
% Underrepresented Racial Minorities [5] [6]	22%	9%	13%	5%	9%
% Hispanic [5] [6]	20%	5%	5%	4%	5%
Publications	Average	Average	Average	Total	Total
In Peer Reviewed Technical Journals	23	6	12	4	49

In Peer Reviewed Conference Proceedings	29	17	8	2	41
Multiple Authors: Co-Authored With ERC Students	32	17	6	5	59
Multiple Authors: Co-Authored With Industry	4	2	1	1	12
Intellectual Property	Average	Average	Average	Total	Total
Invention Disclosures	4	2	1	0	18
Patent Applications	4	1	0	0	12
Patents Awarded	2	0	0	0	2
Licenses (patents, software)	3	0	1	0	0
Education and Outreach Outputs	Average	Average	Average	Total	Total
New Courses Developed	1	2	1	2	3
Currently offered, on-going courses with ERC content	10	5	13	4	11
New Full Degree Programs	0	0	0	0	0
New degree minors or minor emphases	0	0	0	0	0
New certificate programs based on ERC research	0	0	0	0	0

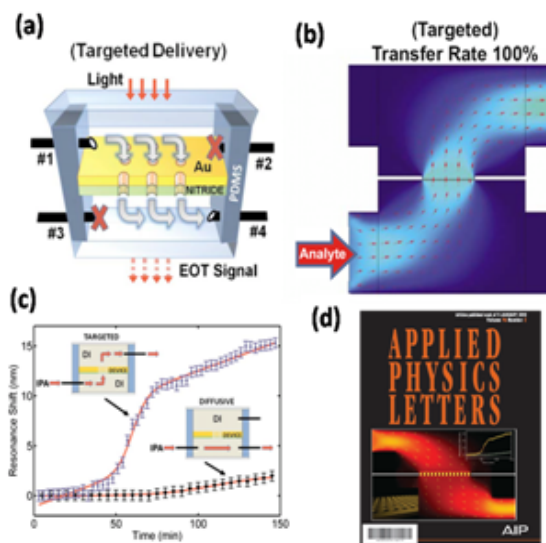
- [1] Includes new support (unrestricted cash, restricted cash, and in-kind donations) from table 9 only. Residual funds carried over from previous years are not included in benchmarking figures.
- [2] Includes total ERC Personnel from table 7.
- [3] Includes participant values from Table 1 Quantifiable Outputs.
- [4] Includes Directors, Education Program Leaders, Thrust Leaders, Senior Faculty, Junior Faculty, and Visiting Faculty from table 7.
- [5] These data do not include K-12 Student or Teacher Participants in the percentage calculations. Demographic data are not collected for K-12 Student or Teacher Participants.
We only collect the total number of K-12 Student and Teacher Participants.
- [6] The percentage calculations are based on the following categories of Personnel only:
Faculty, Graduate Students, Undergraduate Students, REU Students, Directors, Thrust Leaders, Research Thrust Management & Strategic Planning, Administrative Director, and Industrial Liasion Officer.
- [7] Includes Directors, Thrust Leaders, Education Program Leaders, Research Thrust Management & Strategic Planning, Administrative Director, and Industrial Liasion Officer.

1.3 Highlights of Significant Achievements and Impacts

Discovery

1.3.1 Advanced Biosensing Technology for Medical and Military Applications

Rapid detection and surveillance of infectious agents at the point-of-threat is an unsolved challenge for public health, homeland security and armed forces. Traditional technologies relying on enzymatic amplification and labeling techniques require extensive processing time and advanced equipment. Plasmonic nanostructures that can be integrated with LEDs will provide solutions for these problems. Plasmonics offer versatile and powerful detection methodologies due to their unique ability to localize the light below the diffraction limit and to dramatically enhance the local fields for improved detection sensitivity. Nanohole array structures, by acting as a grating, can excite surface plasmon polaritons (SPPs) with normal incident light, such as that emitted by LEDs. To complete the development, the next round of work will focus on incorporating low cost LEDs and simple detectors, paving the way for easily used, low cost, compact biosensors needed for rapid detection of harmful chemical and biological agents for the protection of military and civilian populations.



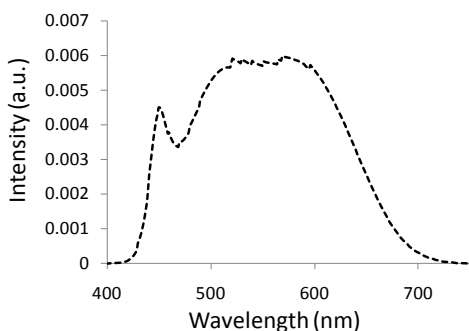
Suspended and integrated plasmonic nanohole array sensor. (APL 11 Jan 2010).

Noble metals on a dielectric will support propagating surface plasmon polaritons (SPP). Since the momentum of SPP is greater than the momentum of light, its direct excitation is typically not possible by an external light source. Recently, plasmonic nanoholes have attracted significant attention with regard to light transmission through the sub-wavelength size holes. Nanohole array structures, by acting as a grating, can excite SPPs with a normal incident light (from LEDs in this work). This technology will enable the fabrication of low cost LED based biosensors for rapid detection of chemical and biological agents.

While this work has been targeted on biosensing, the fundamental technology has wide applications for improving sensor responsivity in general, and also can be integrated with light emitting materials to influence light emitting direction and possibly polarization, making this technology broadly applicable to a wide variety of Smart Lighting applications in illumination and display technologies, as well as in biosensing.

1.3.2 Non-scattering Phosphor Systems for High Efficiency LED Color Conversion

Phosphor conversion of light from blue or UV LEDs is a core component of high efficiency LEDs. Professor Partha Dutta's work has focused on the development of graded composition, very high efficiency optically clear phosphors for advanced LED light sources. Typical white



Emission spectrum of a compositionally graded, non-scattering phosphor plate $(\text{Sr}_x\text{Ca}_{1-x})(\text{Ga}_y\text{In}_{1-y})_2\text{S}_4:\text{Eu}^{2+}$ ($0 < x < 1$; $0 < y < 1$) excited by a blue LED. The plate (about 1 cm square) is on the right.

LEDs are made from powdered phosphor blends, and scattering leads to reduced optical efficiency (scattering losses inside the package) and challenges with phosphor thermal management in high power LEDs. In Year 2, a full spectrum broad wavelength emission white light source fabricated using graded composition optically clear substrate has been demonstrated. The materials system is the based

on the well known high efficiency thiogallate phosphors that are ideally suited for high efficiency white LED fabrication, but historically cannot be used in powder form due to moisture sensitivity.

By tuning the phosphor alloy composition, efficient sources with high color rendering index and/or high color gamut sources could be designed. This approach offers a unique pathway for solving the much needed so-called “green gap” problem. High efficiency saturated color LEDs with emission wavelengths in the vicinity of 555 nm are under development. For high efficacy warm white LEDs, high efficiency red phosphors with emission wavelength in the 600-630 nm range remains a critical requirement. The non-scattering crystal phosphor technology is a promising approach for developing high efficiency red phosphors. The process developed for growing the phosphor substrates or films from high temperature liquid phase provides the opportunity for large area, low cost manufacturing and integration at the die scale or in the luminaires.

Non-scattering high efficiency phosphors open exciting new capabilities for light conversion materials using 1D and 2D photonic crystal structures for light conversion, improved color mixing and more collimated LED emission. Solid, non-scattering phosphors can also incorporate new thermal management strategies for extracting heat due to Stokes shift losses inherent in any phosphor system. Incorporation of plasmonic structures such as those described above could also be used for advanced sensor technology with improved significantly improved sensitivity, and may offer a vehicle for polarized emission from phosphor structures.

1.3.3 Lighting for High Speed Data Communications

Room lighting is fundamentally much better suited than radio for achieving very high data rate densities (Mb/s/m^2) that will be required to satisfy the explosion in the numbers of devices such as smart phones, tablet computers, smart household appliances and data-connected vehicles, as well as the increasing demand for ever higher quality multimedia to be delivered wirelessly. All of these demands can quickly overwhelm the scarce radio spectrum resource, resulting in severe localized congestion, or “wireless gridlock.” In contrast, visible light can be directed and sequestered, enabling multiple independent high capacity links to occupy nearby spaces, thus supporting much larger density of data traffic.

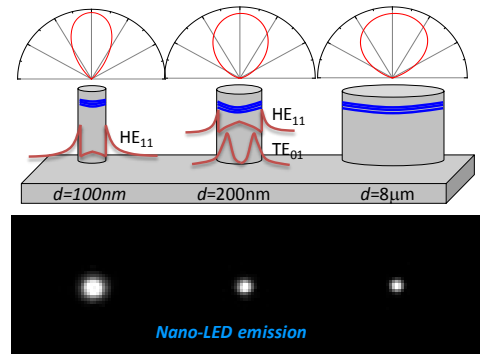
To help realize the promise of visible light communication, the Smart Lighting ERC has completed a prototype and user interface aimed at industrial developers interested in dual use (lighting and communications) applications. The version 1 bidirectional transceiver prototype (called “Smart Light One” or SL1) achieves a data rate of 2Mb/s and data rate density of 2Mb/s/m^2 at distances up to 2m. It has been demonstrated to communicate at capacity while in close proximity to other transmitting transceivers. 40 units have been fabricated and are prepared as kits that serve as a reference design and are being disseminated to universities, ERC industrial partners, and other center researchers. This milestone represents a significant step towards realizing a vision of a low-cost, energy-neutral, bulb replacement that can provide ubiquitous wireless network access for any application requiring lighting.



Front Page of EE Times (May 24, 2010) featuring the Visible Light Communications work of the Smart Lighting ERC

1.3.4 High Efficiency, Single Mode Light Extraction from Nano-Column LEDs

Light extraction from conventional LED structures continues to be a challenge and cannot be easily measured independently of internal quantum efficiency in conventional LED structures. Nano-column LEDs fabricated in Year 2 and excited optically explored the limit of light extraction efficiency by creating single mode emitting devices. Light extraction efficiencies up to 80% were demonstrated without the use of backside mirrors or other extraction technology (encapsulation). For single mode LED structures, a strong preference for top, partially collimated emission was also demonstrated. In addition, the fabrication techniques used to form nano-column LEDs of different diameters provided a process for studying surface carrier leakage, a key issue that needs to be solved for photonic crystal light extraction technology that involves penetrating LED quantum well (QW) structures for significant improvements in light extraction beyond what is achieved today with simple surface photonic crystal or surface roughening processes. With the addition of backside reflectors and top side AR coatings, LED structures with light extraction efficiencies in excess of 90% are anticipated.

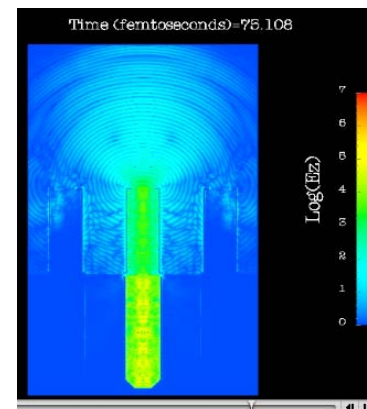


Nano-column LEDs of various sizes used to study light extraction properties of LEDs. The LEDs were optically pumped and very high single mode extraction efficiency and strong preference for top, collimated emission was observed.

1.3.5 First Principles Modeling of Nanowire LED Structures

The FDTD (Finite Domain Time Domain) approach was used to model light emerging from the nanowire LED. Full 3D solutions to Maxwell's equations were computed and the simulation showed light flowing in, and from, the nanowire LED source over the time range 0 to 100 femtoseconds. The simulation showed that the thin (~100 nm) dielectric growth-mask was acting as waveguide for some light polarizations, and that lateral light "leakage" between adjacent nanowire LEDs could be significant. This light "leakage" will create background noise when an adjacent LED is configured as a photodetector. Modeling also reveals the optical modes inside of the nanowire LED structure, and may prove useful in the development of optimized nanowire LED and possibly laser designs.

This is the first reported application of FDTD to modeling of GaN nanowire LEDs, and forms the basis of an extremely useful tool for optimizing the performance of a very wide range of ERC source and detector structures.



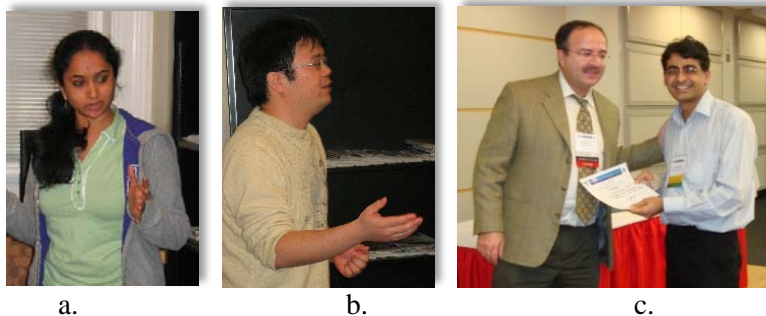
Vertical slice through 3D FDTD light flow simulation of a 3 x 3 nanowire LED array.

Learning

1.3.6 The “Art of the Elevator Pitch”

A student poster competition with a unique approach was held at Boston University in early February, 2010, as part of the ERC’s Industry-Academia Day. The main goals of the event were to develop entrepreneurial skills in students and raise awareness about what is important to industry. In addition, this served as a great opportunity to empower the Student Leadership Council to lead and engage with the ERC’s Industrial Advisory Board (IAB), RPI’s Severino School of Technological Entrepreneurship and BU’s Office of Technology Transfer.

In conjunction with the IAB, the ERC developed a framework for the presentation of research and the judging criteria for the student posters and presentations. Students rehearsed their 90 second ‘elevator pitches’ at the Severino School. They were provided with advice and feedback from faculty and staff, as well as a ‘resident entrepreneur’. ERC faculty advisors helped the students to prepare their presentations and further refine them. Students also held sessions where they delivered their pitches and critiqued each other’s delivery. The Student Leadership Council (SLC) organized the poster competition, produced the poster and abstract templates, held inter-campus meetings, decided on the timeframe for collecting the data, produced the abstract booklet, directed the students to print the posters in a timely fashion, and ultimately selected the elevator-pitch finalists for the public agenda. The poster judging was done by the IAB.



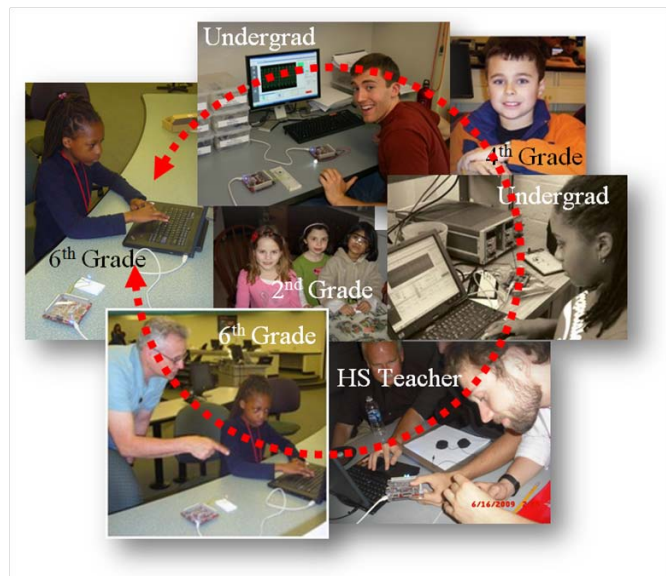
Students (a) and (b) practicing their elevator pitch with feedback from business school entrepreneurs.

(c) The competition winner being congratulated by IAB chair Majeed Foad (Applied Materials) at the Smart Lighting ERC Industry-Academia Meeting.

The elevator pitch competition was very well received by all attendees at the event. When the competition was described at the Engineering Education Grantees Meeting in February 2010, other ERC education and outreach personnel suggested this become a model for other ERCs.

1.3.7 The Mobile Studio Education and Outreach Development Platform:

STEM education with engineering content generally requires expensive, complex equipment and thus is typically built around elaborate facilities with well-trained staff support. The Mobile Studio Platform (using the Mobile Studio I/O board) makes it possible for students to carry their enthusiasm for engineering and science from the classroom to any place they have a computer. It gives them access any time and any place to a full electronics laboratory for only the price of a textbook. Students have a portable lab in which tinkering is again possible; requiring only a spark of interest - not a big budget. This simple yet powerful teaching tool has been shown to be an interconnected framework on which education and outreach experiences can be built starting at any level from Pre-K to advanced graduate studies. Ideas developed for a summer program for high school, for example, have migrated to first year courses and back to high school. Experiments and Demonstrations originally applied in an upper level undergrad course are now utilized in elementary and high school outreach. Elementary school outreach, with its large numbers of energetic, young minds trying things that no one had imagined, produced new engineering and science experiences for upper level undergrads. This tool is now being developed with a host of age appropriate LED lighting educational modules useful for engineering educational modules where experimental results can be seen.



The Mobile Studio Board sparks interest in science and engineering across all levels of students.

Research Infrastructure

1.3.8 Modeling of Light Flow for Visible Light Communications

Due to the rapid ongoing advancement of solid state lighting, and the capability of white illumination LEDs to be controlled and rapidly switched, there is much interest in creating dual use systems that provide both lighting and wireless data access through visible light communications (VLC).

Computer-based modeling can provide invaluable aid in the design of such systems by predicting communication and lighting performance prior to prototyping and installation.

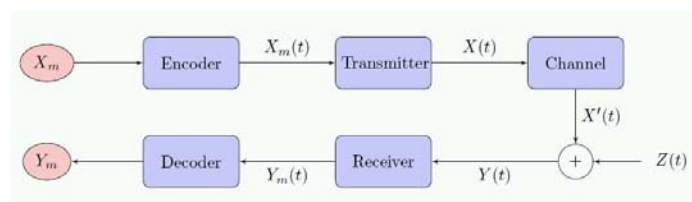


Figure 1: VLC system components modeled by CandLES

Communication and Lighting Emulation Software (CandLES), is a detailed model of the entire VLC/lighting system and its operating environment. CandLES integrates models of individual components, including the modulation, transmitters, optics, channel, noise, interference, receivers and decoding, into an overall system model. The software evaluates communications performance including achievable data rate, error rate and coverage, as well as lighting performance with respect to illumination coverage.

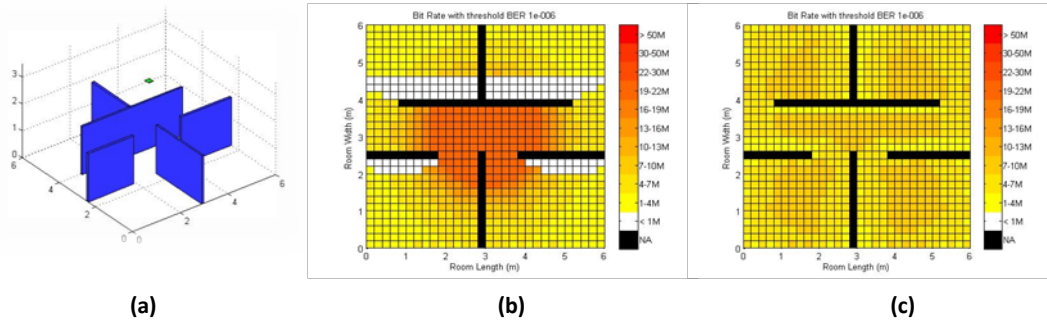


Figure 2: VLC in a typical office with cubicles, modeled with CandLES. (b) A single 5W LED transmitter at the center of the ceiling, and (c) four 1.25W transmitters spaced evenly on the ceiling.

The power of CandLES as a design tool lies in simultaneously considering all the individual components as well as the system as a whole. This allows a communications engineer to identify specific bottlenecks affecting performance, in order to target design improvements where they are most effective. It allows us to test robustness of the system to changes in the environment (room size, orientation, shadowing objects, wall colors, noise), or in operating requirements (desired brightness, field of view). As a result, CandLES helps uncover design pitfalls before a costly and time-consuming prototype is fabricated. After fabrication, it can help an installer of the system find best placement of lamps/transmitters throughout a room. This tool has been ported to RPI for use in modeling lighting in the Smart Spaces test bed.

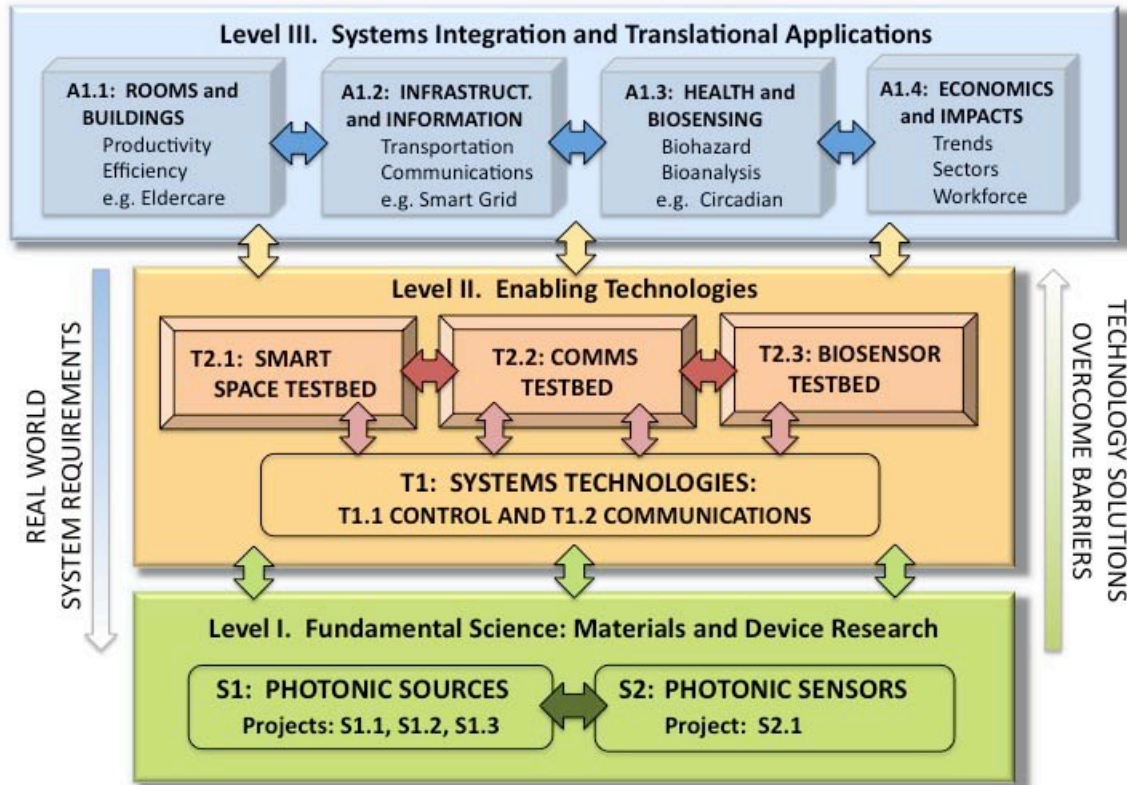


Figure (1). 3-Plane Strategic Planning Chart for Year 3