Solid State Lighting Program
FINAL REPORT

October 31, 2011

High Efficacy Integrated Under-Cabinet Phosphorescent OLED Lighting Systems

Work Performed Under Agreement:
DE-EE0000626

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A. Project Summary

In this two year program Universal Display Corporation (UDC) together with the University of Michigan, Teknokon, developed and delivered an energy efficient phosphorescent OLED under cabinet illumination system. Specifically the UDC team goal was in 2011 to deliver five (5) Beta level OLED under cabinet lighting fixtures each consisting of five 6" x 6" OLED lighting panels, delivering over 420 lumens, at an overall system efficacy of >60 lm/W, a CRI of >85, and a projected lifetime to 70% of initial luminance to exceed 20,000 hours.

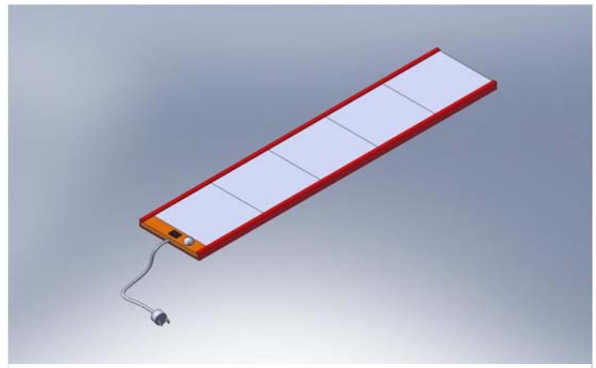


Figure 1: Rendering of proposed thin Luminaire with five 6" x 6" OLED panels.

During the course of this program, the Team pursued the commercialization of these OLED based under cabinet lighting fixtures, to enable the launch of commercial OLED lighting products. The UDC team was ideally suited to develop these novel and efficient solid state lighting fixtures, having both the technical experience and commercial distribution mechanisms to leverage work performed under this contract. UDC's business strategy is to non-exclusively license its PHOLED technology to lighting manufacturers, and also supply them with our proprietary PHOLED materials. UDC is currently working with several licensees who are manufacturing OLED lighting panels using our technology.

B. Accomplishments

All Milestones were completed on time.

- **Demonstrated a white PHOLED pixel with a luminous efficiency of 83 lm/W at 1500 cd/m^2 with a CRI of 83 and a color coordinate of (0.442, 0.419).**
- **Demonstrated a 15cm x 7.5cm white OLED lighting panel with a luminous efficiency of 65 lm/W at 1000 cd/m^2 and a color coordinate of (0.427, 0.432).**
- **Demonstrated a 15cm x 15cm white OLED lighting panel with a luminous efficiency of 66 lm/W at 1000 cd/m^2 and a CRI or 79**
- **Delivered 2 OLED under-cabinet luminairies**
  - **Each luminairie contained 10, 15cm x 7.5cm OLED lighting modules**

- **The OLED luminairie efficacy was 56 lm/W at 420 lumens (2200 cd/m^2)**
- **Luminaires CRI was 85**

- **Completed OLED Lighting Commercialization Roadmap**

C. Milestones and Deliverables

Year 1		
Milestone 1	Report describing results of OLED pixel demonstrating 80 lm/W and CRI >80 at 1,500 cd/m^2	Completed on time Month 9
Milestone 2	Design document outlining details of OLED lighting luminaire, including OLED panel and electronics design	Completed on time Month 12
Milestone 3	Report of OLED lighting 6” x 6” panel > 65 lm/W efficacy, lifetime LT70 > 20,000 hours with CRI > 80	Completed on time Month 12
Year 2		
Milestone 4	Report of OLED lighting 6” x 6” panel > 85 lumens, > 65 lm/W efficacy, lifetime LT70 > 20,000 hours with CRI > 85	Completed on time Month 18
Milestone 5	Deliver 5 OLED under counter luminaires that exceed 420 lumens, > 60 lm/W efficacy, LT70 > 20,000 hours with CRI > 85.	Completed on time Hardware deliverable Month 24
Milestone 6	Deliver a commercialization roadmap outlining path to launch of OLED under-counter lighting products.	Report, Month 24

D. Program plan and schedule

	Tasks	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
		Quarters							
Phase 1	High Efficacy PHOLED								
	Task 1.0 - Optimize PHOLED Design	■	■	■	■	■	■		
Phase 2	Luminaire Design								
	Task 2.0 - Panel Design		■	■					
	Task 3.0 - Power supply Design			■	■				
	Task 4.0 - Fixture Design			■	■				
Phase 3	High Outcoupling Efficiency								
	Task 5.0 - Achieve >50% outcoupling	■	■	■	■	■	■	■	■
Phase 4	Luminaire Fabrication								
	Task 6.0 - Panel fabrication						■	■	
	Task 7.0 - Luminaire integration							■	■
	Task 8.0 - Characterization								■
Phase 5	Commercialization Strategt								
	Task 9.0 - Commercialization roadmap							■	■

E. Background

The goal of this project was to deliver an integrated OLED luminaire for under-cabinet lighting applications that exceeds the performance specifications outlined in the DOE 2008 Multi-Year Program Plan. Specifically we planned to deliver a prototype luminaire having the performance outlined in Table 1.

METRIC	DOE 2011 Projected Target	UDC Team Goal for 2011 PHOLED luminaire
Efficacy – Commercial luminaire (lm/W)	46	60
OEM Panel Price ($/klm)	37	24
CRI	85	85
Luminance	1,000	1,500
Lamp lifetime (LT70) (hrs)	20,000	20,000

Table 1: Rendering of proposed thin Luminaire with five 6" x 6" OLED panels.

Table 1 also provides a comparison of UDC planned versus DOE projected target luminaire performance**.** Table 2 shows the specific proposed product performance for our PHOLED under cabinet luminaire.

METRIC	**Proposed product Specification**
Efficacy –(lm/W)	60
CRI	85
Luminous flux (lumens)	420
Power supply requirements	117 V AC
Size	0.4” x 6” x 30”
OEM Lamp Cost ($/m^2)	$15
Projected luminaire cost ($)	$35
Lamp lifetime (LT70) (hours)	>20,000

Table 2: Proposed specification for PHOLED under cabinet luminaire

Our luminaire deliverable was designed to meet or exceed all the performance requirements outlined in the solicitation, specifically achieving 60 lm/W efficacy. To achieve the 420 lumen output to be competitive with current fluorescent fixtures, the OLED panels will be operated at approximately 1,500 cd/m^2, representing a 50% increase in luminance over typical luminance values. The overall luminaire consists of three key components: drive electronics, OLED lighting panel, and the mechanical fixture. Each component has its own efficiency and cost factors.

	Efficacy (lm/W)
Commercial OLED pixel	80
OLED panel (6” x 6”)	72
Driver efficiency	90%
Fixture efficiency	92%
Luminaire efficacy	**60**

Table 3: Efficiency of PHOLED luminaire and components

The luminaire efficiency will be the *product* of the three component efficiencies. The overall luminaire is being designed to consist of 10 individual 6” x 3” lighting panels within the luminaire fixture (under cabinet system), operating from a 117VAC line input. Assuming an 80 lm/W commercial pixel (UDC has already achieved > 100 lm/W lab pixel), our analysis (see section A.3) shows that this will result in a > 72 lm/W 6” x 6” panel. Allowing for electronics and fixture efficiencies of 90% and 92% respectively, we arrive at an overall 60 lm/W overall luminaire efficacy – see Table 4.

Previous Work and Technical Strategy

UDC is a world leader in the field of organic light emitting materials, device, and process research and development. UDC has a team of 45 scientists and engineers focusing in these areas, and longstanding sponsored research program with Professor Stephen Forrest and his research team at the University of Michigan; a pioneer in PHOLED research. Today, UDC and our research partners are recognized as leaders in the area of organic electronics research, and their development for commercial applications. For the past ten years, the team has focused exclusively on developing state-of-the-art PHOLED technology.

Our team's invention, followed by continuing development of phosphorescent OLEDs is a key technology that will enable OLEDs to become an efficient and viable general illumination light source. Today UDC's PHOLED technology is acknowledged as a critical element to the success of OLEDs for both flat panel display and lighting applications. Furthermore, the compatibility of OLEDs for use on flexible substrates pioneered by our team opens up the possibility for a new generation of illumination sources that are conformable, rugged and extremely light weight. In addition, the ability to produce these PHOLEDs on plastic or metal substrates enables the use of roll-to-roll manufacturing techniques to significantly reduce manufacturing costs. Hence, there are many compelling arguments for pursuing phosphorescent OLEDs for the next generation of low cost solid-state light sources.

Over the last 5 years, UDC has demonstrated consistent improvements in the power efficacy of white PHOLEDs from 5 lm/W to 102 lm/W. In 2008, UDC successfully demonstrated an all phosphorescent white organic light emitting diode (WOLED™) with a power efficacy of 102 lm/W at 1,000 cd/m^2. These high efficacy values are comparable to fluorescent lamps, especially when the fluorescent luminaire efficiency is taken into consideration. Table II lists the 102 lm/W device characteristics and compares them to targets to achieve a 150 lm/W Energy Star device by 2015, and the goals of this effort. Our high-efficacy device was enabled by lowering the device operating voltage, increasing the outcoupling efficiency to 40% from 20%, and by incorporating highly efficient phosphorescent emitters that are capable of converting nearly all current passing through a WOLED into light. Warm white emission from the device has a color rendering index of 70 at (0.41, 0.46), and this color was chosen because it more closely resembles the color of Illuminant A standard incandescent, which WOLEDs may replace in the lighting industry.

This program had a target efficacy of 65 lm/W with a CRI of 85 for individual PHOLED pixels by 2011 to enable an overall luminaire efficacy of 60 lm/W, including losses from drive electronics, and this goal was achieved by addressing three key efficiency parameters. For a Lambertian emission OLED source, where V = operating voltage and

η_{lum} is luminance efficiency (cd/A) (A=Amps), the power efficacy (η) is given by $\eta = \eta_{lum} \cdot \pi / V$, and $\eta_{lum} = k \cdot \eta_{int}\, \eta_{out}$, where η_{int} = internal quantum efficiency (% excitons to photons), and η_{out} = outcoupling efficiency (% of photons emitted into air to generated photons), and k is a constant dependent on the photopic response of the human eye; hence,

$$\eta = \frac{k \cdot n_{lum} \cdot n_{out} \cdot \pi}{V} \qquad (1)$$

As a result, power efficiency is a function of internal quantum efficiency, $\boldsymbol{\eta_{int}}$**,** light extraction, $\boldsymbol{\eta_{out}}$, and voltage, **V.** Thus, to improve device performance, advances in these areas are required. To realize a 65 lm/W pixel, our plan is to achieve the following individual performance metrics: (a) 90% internal quantum efficiency, (b) <3.8 V operating voltage at a target luminance of 1,000 cd/m^2, and (c) 40% outcoupling efficiency.

F. Phase 1 - High Efficacy PHOLED

We reported that on our standard test device, a 2mm^2 pixel, we achieved 83 lm/W with a CRI of 83 at 1,500 cd/m^2. See Figure 2. This result completed Milestone 1. These devices were measure using a 2X outcoupling enhancement lens. The LT 70 was measured under accelerated condition and was extrapolated to Lo=1,000 nits using an acceleration factor of 1.4. The results are summarized in Table 4.

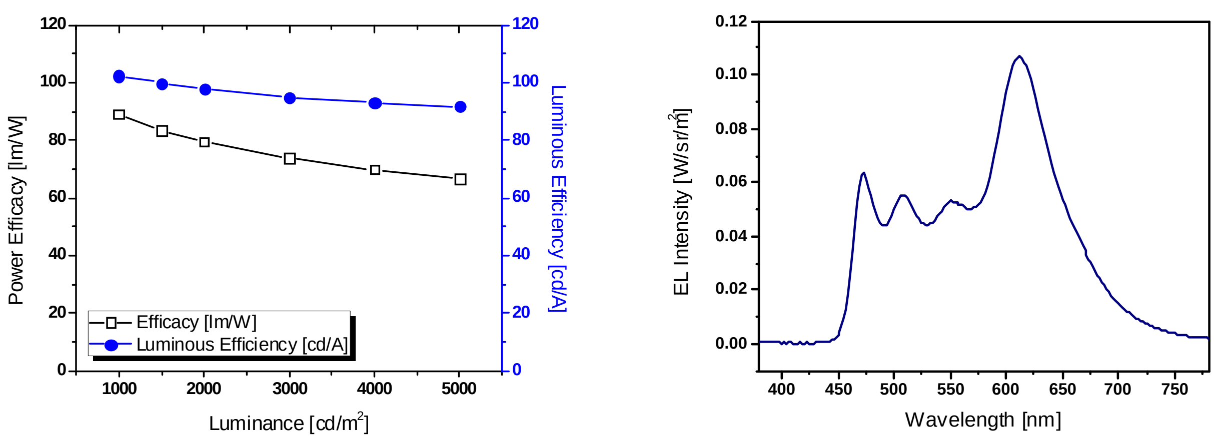


Figure 2: Milestone 1 test results for the white OLED 2mm^2 pixel achieving 83 lm/W with a CRI of 83 at 1500 cd/m^2 exceeding the milestone goals.

	Achieved	Achieved	Goal
	At 1,000 cd/m^2	**At 1,500 cd/m^2**	**At 1,500 cd/m^2**
Efficacy	**89 lm/W***	**83 lm/W***	**80 lm/W**
CRI	**83**	**83**	**>80**
EQE	49%	48%	
Voltage	3.61 V	3.75 V	
1931 CIE	(0.442, 0.419)	(0.442, 0.419)	
CCT	3040 K	3040 K	
LT70 [hrs]	10,000	6,000	

Table 4: Summary of Milestone 1 results (April 2010)

Early in this program, we demonstrated a large area lighting panel with an efficacy of 50 lm/W and a CRI of 87 at 1000 cd/m^2. Two key developments were critical for this early achievement. The first was the development (outside of this program) of a new light blue phosphorescent emitter, and the second was an improved panel layout design. The new blue emitter has also allowed us to simplify the OLED structure in the organic stack to six layers. See Figure 3. To further increase the efficacy of the lighting panel, we optimized the panel and device design to further reduce the voltage, and increase light output. These included higher conductivity buss bars and refinements of the layer thicknesses in the organic stack.

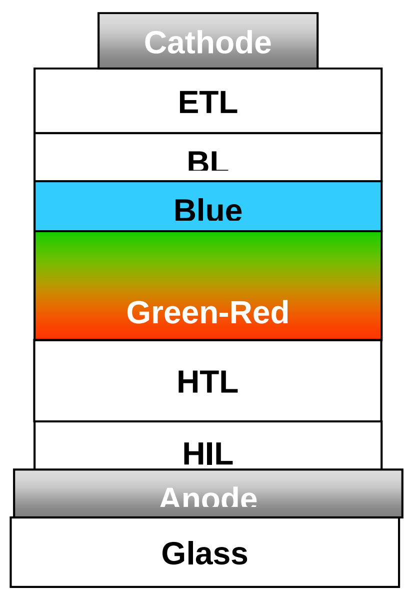


Figure 3: 6 layer organic structure used for the white lighting panels.

Milestone 3 was completed on time in month 12, although on a 6" x 3" panel. The milestone summary was submitted in August 2010 as part of the July monthly summary report. We achieved a performance of a white phosphorescent OLED (PHOLED) under-cabinet lighting panel at 65 lm/W at 1000 nits measured in an integrating sphere using an light extraction block. The device voltage was 3.7 V with a current density of 1.31 mA/cm^2. The CIE coordinates are (0.427, 0.432). A summary of the test results can be found in Table 5.

The under-cabinet lighting panel measured was 6”x 3” using the panel layout described in the design document. It was found that inverting the light extraction block such that the side with the larger area was facing up increased the efficacy by approximately 3% over having the large area of the block facing down. See Figure 4 and Table 5 for summary of the results.

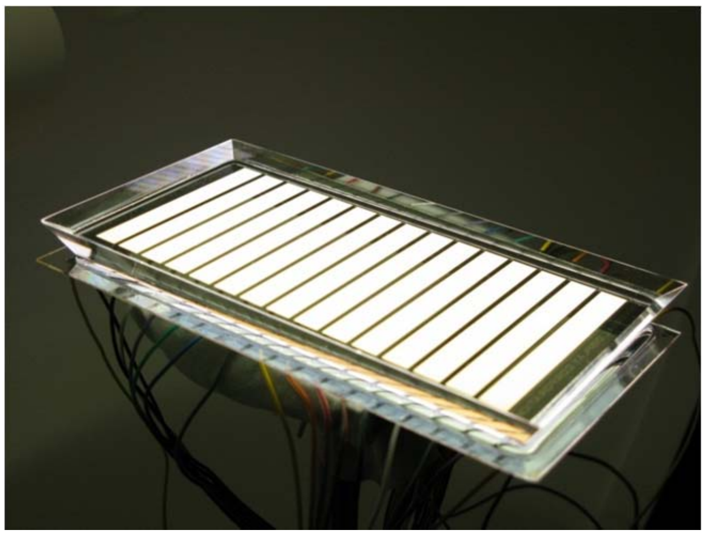


Figure 4: 6” x 3” lighting panel used for Milestone 3

	No Outcoupling (Normal Incidence)	Light Extraction Block (Integrating Sphere)
Area	6” x 3”	6” x 3”
Efficacy	36 lm/W	65 lm/W
Voltage	3.9 V	3.7 V
CRI	80	80
1931 CIE	(0.456, 0.429)	(0.427, 0.432)
CCT	2900 K	3380 K
Efficacy Enhancement	1.00x	1.78x

Table 5: Summary of the results of the 15cm x 7.5 cm lighting panel for Milestone 3 (July 2010)

Milestone 4 was completed on time in month 14. A 15cm x 15cm white OLED lighting panel that has achieved efficacy of 66 lm/W at 1,000 cd/m^2. This milestone was submitted in December 2010 as a separate Joule highlight. The lighting panel was measured in an integrating sphere using a light extraction block with index matching fluid. The lighting panel CRI was 79 and the color temperature was 3,650K. A summary of the lighting panel performance is in the Table 6.

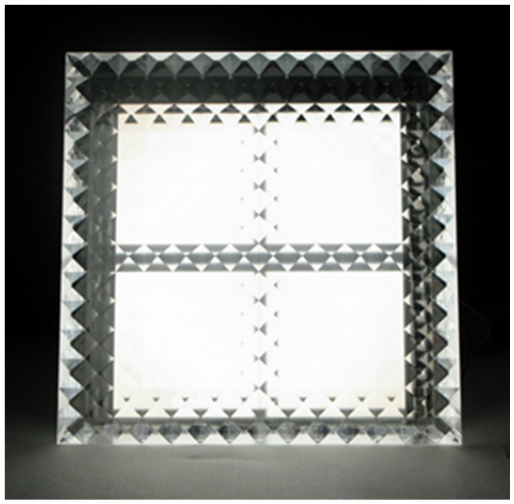


Figure 5: 15cm x 15cm OLED lighting panel that achieved 66 lm/W at 1,000 cd/m2 with an outcoupling enhancement lens.

	No Outcoupling (0° Incidence)	**Light Extraction Block (Total Emission)**
Efficacy	**32 lm/W**	**66 lm/W**
Voltage	4.00 V	3.74 V
CRI	**81**	**79**
1931 CIE	**(0.446, 0.429)**	**(0.415, 0.438)**
CCT	**3050 K**	**3650 K**
Efficacy Enhancement	1.00x	2.06x

Table 6: Summary of the results for for the 15cm x 15cm OLED lighting panel for Milestone 4 (October 2010)

G. Phase 2 - Luminaire Design

Design Strategy

During the design phase of this project, several meetings were held with the team members from UDC and Technokon. Key features that resulted from these meetings have been included in the design are as follows:

1. The panel layout is designed to be operated as a 6"x 6" panel, or cut into 2 pieces and operated as 3"x 6" panels.
2. The core design principle of the under-cabinet lighting system is modularity.
3. Each light module contains a 3 inch by 6 inch OLED
4. The power to the OLED power supply will be provided from a standard 117VAC electrical outlet and capable of powering up to 10 light panels/modules.

Panel Layout

We established a model for the basic one-dimension OLED lighting device. Using Ohm's law and the OLED electro-optical characteristics, we can relate the current flowing through each OLED to the corresponding luminance level and voltage. Therefore, the panel uniformity defined as (maximum luminance-minimum luminance)/maximum luminance, and the power loss can be calculated. If we specify a maximum non-uniformity criteria, the device dimension, i.e., the length of any pixel element, can be optimized to achieve the lowest power loss, with the highest aperture ratio.

Using IVL data from a phosphorescent white OLED pixel we calculated and resistive power loss for a highly efficient phosphorescent light panel under various conditions. The results of this calculation are shown in Table 7.

Luminance Uniformity	Average Luminance (Includes Outcoupling) [cd/m^2]	Sheet Resistance [Ω/sq]	Furthest Distance from Anode Contact (d) [cm]	Panel Efficacy [lm/W]	Pixel Efficacy [lm/W]	Resistive Power Loss for Calculated Pixel Area [%]
10%	3,000	10	1.45	41.24	41.60	0.865%
20%	3,000	10	2.15	40.83	41.60	1.851%
10%	3,000	15	1.19	41.24	41.60	0.865%
20%	3,000	15	1.75	40.83	41.60	1.851%
10%	3,000	20	1.03	41.24	41.60	0.865%
20%	3,000	20	1.52	40.83	41.60	1.851%
10%	5,000	10	1.24	37.67	38.04	0.973%
20%	5,000	10	1.84	37.23	38.04	2.129%
10%	5,000	15	1.01	37.67	38.04	0.973%
20%	5,000	15	1.50	37.23	38.04	2.129%
10%	5,000	20	0.88	37.67	38.04	0.973%
20%	5,000	20	1.30	37.23	38.04	2.129%

Table 7: Simulation results for a large area light panel with phosphorescent emitters

The layout used for the under cabinet lighting panel has 30 electrodes, each 8mm wide by 50mm long (Figure 6). Each electrode has a bus line around the active area to improve the effective anode conductivity and provide its own anode contact. The anode contacts can be easily bussed together with the adjacent electrodes. Also, the individual anode contacts allow for ease of debugging and testing good pixels on panels with some defective pixels. Further, this panel designs allows for the panel to be operated as a 6”x 6” panel, or cut into 2 pieces and operated as 3”x 6” panels.

The distance from the anode for each pixel in this design can be defined as the distance from the bus lines. Applying the data in the above Table to this panel design, we see that the luminance non-uniformity will never be greater than 10%, since the farthest distance from the bus line in this design will never be greater than 0.4cm, which is half the width of the pixel. Our typical anode sheet resistance is approximately 15 ohms / square.

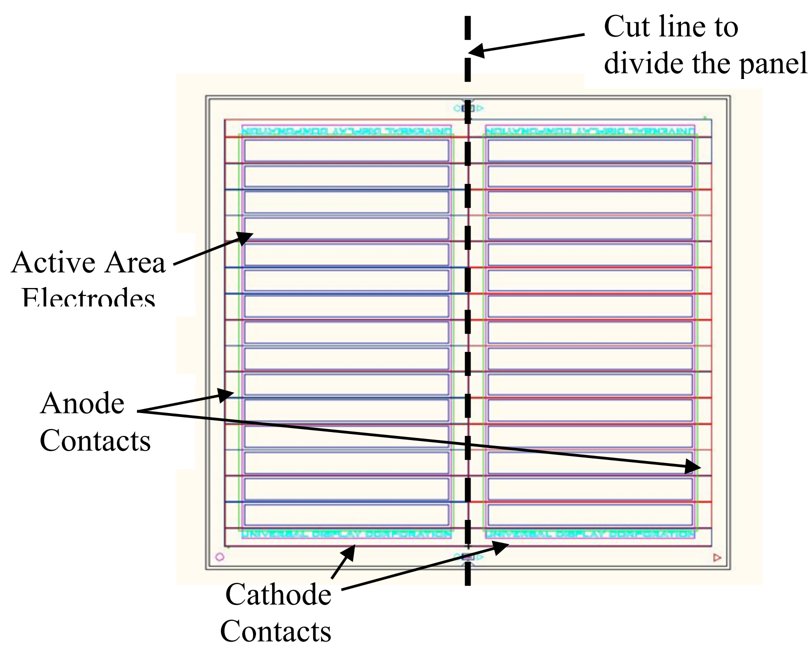


Figure 6: Layout for the under-cabinet lighting panel.

Under-Cabinet Fixture Design

The core design principle of the under-cabinet lighting system is modularity. The system is made up of light modules, a control module, various connectors and cables, and cord wraps and anchors to provide cable management. See Figure 7.

Each light module contains a 3 inch by 6 inch OLED panel sandwiched between a backing plate and an outcoupling lens, surrounded by an aluminum frame. See Figure 8. The design allows for the use of either a thick outcoupling lens for maximum light extraction and efficiency, or a thin outcoupling lens for a more refined aesthetic. All four sides of the light module have a plug receptacle which is used for both power distribution and as a mounting point. The light modules can be arranged edge-to-edge to form a tight grid, spread apart and connected via cables, or a combination of both. When panels are abutted edge-to-edge, they are connected using an edge-connection plug. Any exposed, non-abutting edge receives a mounting plug which contains a screw hole for affixing to a surface, such as the underside of a cabinet. The modular nature of the system leaves open the possibility of other types of mounting plugs, utilizing magnets or removable adhesive, for instance.

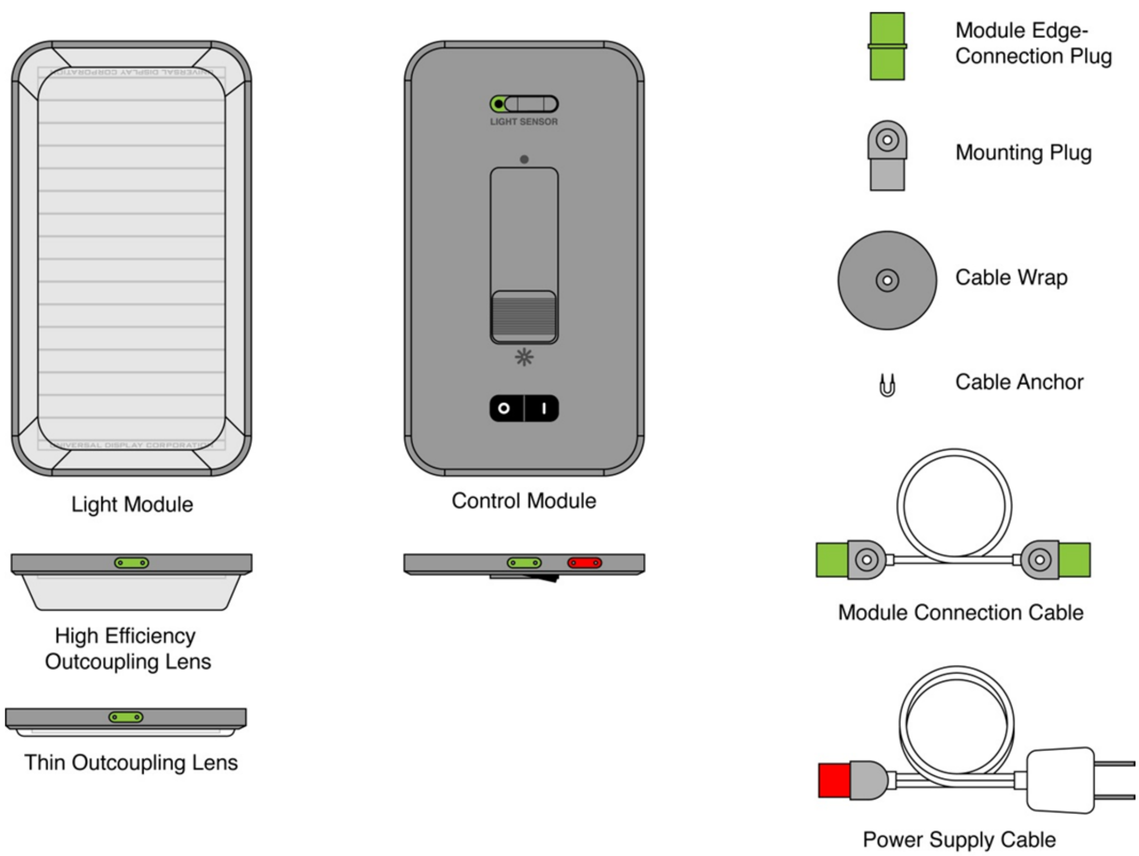


Figure 7: The components of the under-cabinet lighting system

Figure 8: The components of the light module. From top to bottom: backing plate, OLED panel, outcoupling lens, aluminum frame.

Several different lens designs were tested with the OLED lighting panels. The lenses were all machined from clear acrylic material and were tested on top of the lighting panel that is designed for the under cabinet fixture. Each lens had a slightly different shape. Some of the lenses had a patterned machined into the top surface, a ridge pattern or a pyramid pattern. The ridge pattern has parallel V cuts in a single direction and the pyramid pattern has perpendicular V cuts in creating a pyramid structure on the top surface. See Figure 9 for a picture of each type of surface cut. A summary of the lens testing results is in Table 8.

Figure 9: The top picture show a lens that has the ridge pattern which is a V cut in a single direction. The bottom picture has the pyramid pattern which is a V cut in both directions.

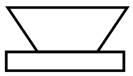
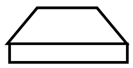
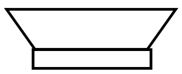
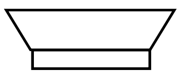
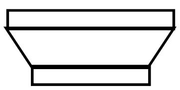
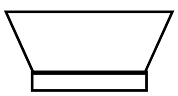
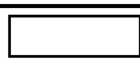
Lens Size	Lens Shape	Top surface Pattern	Block Thickness	Efficacy [lm/W] (at 1,000 nits)	CIE (x, y) (at 4,000 nits)
No Lens				36	(0.456, 0.429)
Diffuser Sheet				55	(0.429, 0.434)
6” x 3”		No Pattern	0.5”	64	(0.418, 0.431)
6” x 3”		No Pattern	0.5”	62	(0.420, 0.431)
6.5” x 3.5”		Pyramid Pattern	0.5”	64	(0.414, 0.430)
6.5” x 3.5”		Ridges Pattern	0.5”	64	(0.414, 0.430)
6.5” x 3.5” Thicker		Ridges Pattern	0.7”	65	(0.413, 0.429)
6.5” x 3.5” Thicker		Ridges Pattern	0.7”	68	(0.412, 0.429)
Square Block		No Pattern	0.5”	59	-

Table 8: Summary of the lens testing results

Efficient Power Supply and Electrical Design

OLED’s are DC current driven devices and the ballast or driver circuit for the OLED based under- counter lamp needs to provide the appropriate electrical drive. We designed the system to utilize a series string of OLED pixels. This will result in a drive requirement of between 50-100mA at approximately 45VDC which must be derived from a standard 117VAC supply.

Two approaches were considered for the OLED driver. Originally, we conceived an approach that involves using a switch mode power supply based upon a power factor controller IC, the block diagram for which is shown below in Figure 10. The details of the diagram need to be slightly modified to account for the fact that the OLED string requires a lower voltage across it than would be otherwise developed, but the essential concept is that that the current would be sensed and controlled by the power factor controller IC. It is comparable in complexity and cost to the ballast circuits used in compact fluorescent bulbs.

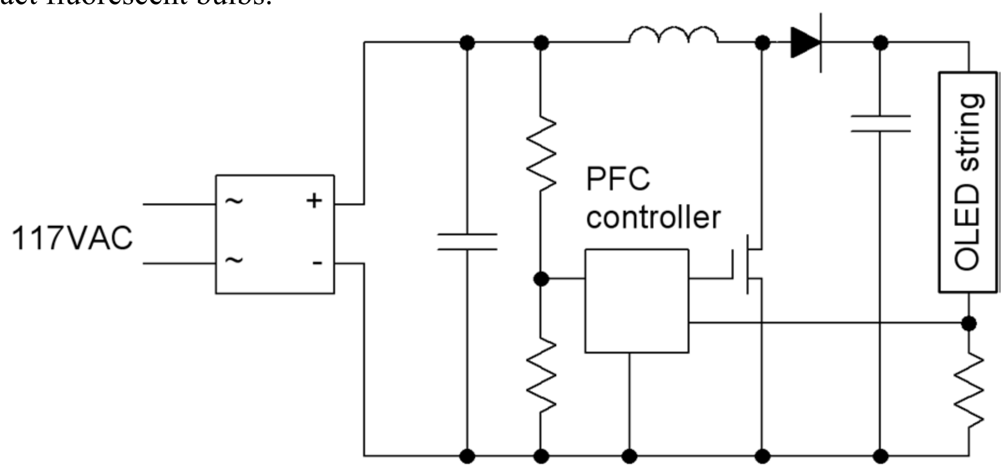


Figure 10: Block diagram for the switch mode power supply based upon a power factor controller IC

However, the fact that the OLED string voltage is substantially lower than the peak AC voltage lends itself to a second design approach that is even simpler and lower in cost. It is shown below in Figure 11.

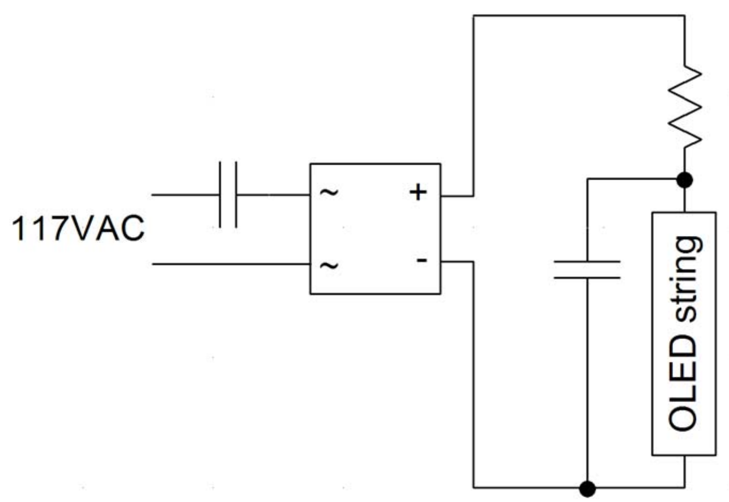


Figure 11: Block diagram for the simple low cost driver circuit

In the simple circuit, the capacitor before the bridge rectifier acts as a relatively high impedance that sets the average current that flows through the OLED string. Given that the impedance is capacitive, the effect is to lose essentially zero power in the series impedance based current regulation circuit. There are some disadvantages to the simple approach though, the main ones being the phase angle of the current relative to the voltage, introducing some susceptibility of the circuit to voltage transients, and the brightness of the illumination being a function of the power supply voltage. However, given the simplicity, cost and efficiency advantages, managing the voltage transient issue (e.g., with a MOV transient absorber) seems appropriate. It also seemed unlikely that the load presented by the combination of ballast and OLED string will present a significant problem for power companies given the small currents involved and the low harmonic content of the semi-sinusoidal current waveform. Finally, customers are already accustomed to having the illumination being a function of power supply voltage, so this is no different from what is considered normal.

In summary, both circuit topologies were investigated. One is electronically more perfect in that it presents a nearly ideal load to the AC power supply and regulates illumination, but has a higher complexity and cost, and, by itself, has a lower efficiency. The other is electronically less perfect, but is "simple," very low cost and, by itself, is more efficient.

H. Phase 3 – High Outcoupling Efficiency

Phosphorescent OLEDs with an internal quantum efficiency (η_{IQE}) of 100% already approach the efficiency of fluorescent lamps. However, due to the high refractive index of organic materials and the optical confinement and internal reflection that results, the light outcoupling efficiency, η_{out}, for conventional OLEDs is limited to ~20%. During tis program we worked with the University of Michigan to improve the outcoupling efficiency of PHOLED devices.

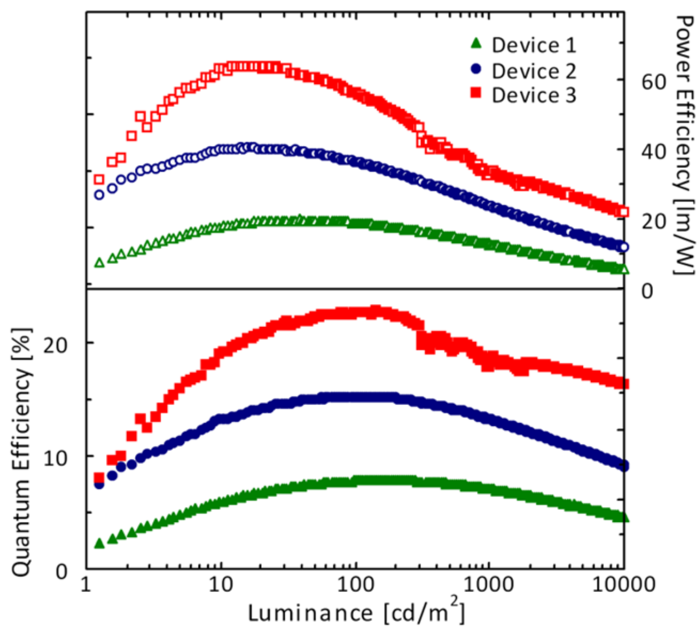


Figure 12: Luminous power (top) and external quantum (bottom) efficiencies as functions of total OLED luminance in the forward-viewing direction. Device 1 (triangles) is a conventional OLED structure, Device 2 (circles) is Device 1 measured using a an index matching liquid (IML) between the glass substrate and the photodetector to outcouple all substrate modes, and Device 3 (squares) is for an UltraLIG using an IML.

We focused on silica (SiO_2) low-index grid (LIG, n = 1.45) embedded in the organic layer of the OLED, which previously has been shown to efficiently scatter waveguided light into the substrate and forward viewing direction. Further investigation using numerical full-wave electromagnetic field simulations revealed that the outcoupling should significantly increase as the refractive index of the LIG material is reduced to that of air, theoretically allowing $\eta_{EQE} > 50\%$.

External quantum and luminous power efficiencies are plotted as functions of luminance in Figure 12 for three devices: (1) a conventional OLED with no outcoupling, (2) a conventional OLED with IMF glass mode outcoupling, and (3) an UltraLIG ($n \approx 1.15$) based OLED with IMF. Peak forward-viewing efficiencies of $\eta_{EQE} = 22.5 \pm 0.3\%$ and $\eta_P = 64 \pm 3$ lm/W are obtained for Device 3 compared to $\eta_{EQE} = 7.8 \pm 0.1\%$ and $\eta_P = 20 \pm 2$ lm/W for the conventional Device 1, and $\eta_{EQE} = 15.4 \pm 0.2\%$ and $\eta_P = 40 \pm 2$ lm/W for glass outcoupled Device 2. By comparing the light output of devices 2 and 3, a 48 ± 4% increase in light extraction from waveguided modes by the UltraLIG is observed at a luminance of 100 cd/m^2, compared to 34 ± 2% enhancement obtained previously with an $n = 1.45$ LIG.

The enhancement remains relatively constant (2.9 ± 0.3 total and 1.45 ± 0.04 waveguide outcoupling) at luminances between 10 and 1000 cd/m^2 (see Figure 13); however, below and above these values, the enhancement increases (Figure 13 inset) due to the unavoidable small variations between devices being amplified. In the low luminance regime near the device turn on, the increase appears to be unrelated to the UltraLIG, as it is present in the ratio of the glass-outcoupled device η_{EQE} to that of the control. It is possible that charge imbalance shifts the position of the emission region, affecting the light extraction efficiency from the waveguide modes. On the other hand, at high current densities, the device efficiency also decreases; here, small differences in film morphology or other effects may alter the efficiency roll-off behavior. As expected, the power efficiency enhancement follows the same trends as η_{EQE}.

Summarizing this work on the UltraLIG, an ultra-low-index grid is fabricated by obliquely depositing a highly porous but nearly isotropic film of SiO_2 with the resulting index of $n \approx 1.15$. Patterning of the UltraLIG was accomplished using standard lithographic techniques to define the grid pattern onto which a phosphorescent OLED is evaporated. The embedded grid efficiently scatters light normally trapped in the high-index layers of the OLED, with nearly 50% more light extracted from waveguided modes, an enhancement of ~1.4 over a previously demonstrated $n = 1.45$ grid. The improvement is nearly constant across a wide range of luminance and is in

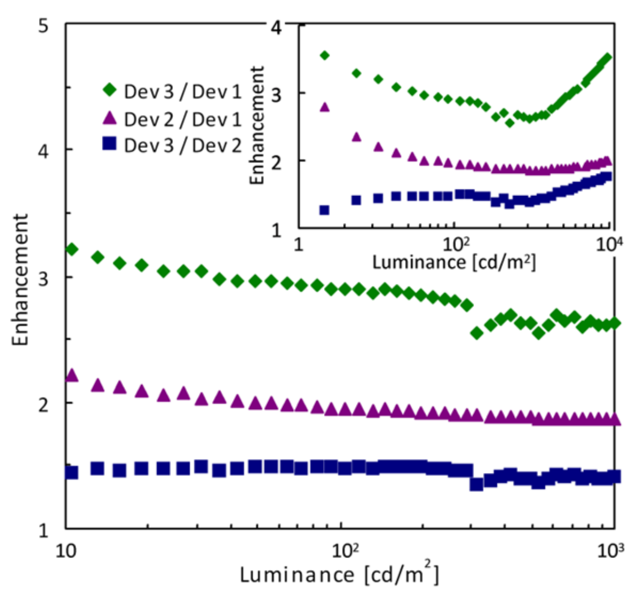


Figure 13: Device efficiency enhancement ratios as functions of luminance. Squares are the ratio of outputs of Device 3 to Device 2 (see Fig. 3), triangles compare Device 2 to Device 1, and diamonds compare the UltraLIG device (3) to a conventional OLED

reasonable agreement with prior full-wave electromagnetic simulations. Moreover, when glass mode light is additionally outcoupled at the substrate-air interface by an index matching fluid, a three-fold enhancement in external quantum and luminous power efficiencies is produced compared to a conventional OLED.

Further work was performed with LIG devices using $2mm^2$ test pixels. LIG structure was patterned around several pixels on the same substrate reducing the active area to 36% and 69%. A white PHOLED devices were grown on the pixels and tested in an integrating sphere at 1000 cd/m^2. The test results were compared with a reference pixel from the same substrate. The results showed that there was an efficacy enhancement for both LIG pixels. The pixel with the smallest fill factor had the largest enhancement over the reference pixel at 1.19x, while the larger fill factor had an enhancement of 1.09x. A summary of the test results can be found in Table 9.

Integrating Sphere At 1,000 cd/m^2 With Macroextractor	**Voltage [V]**	**LE [cd/A]**	**PE [lm/W]**	**CIE (x, y)**	**CRI**	**CCT [K]**	**Efficacy Enhancement**
Reference WOLED	3.8	103	85	(0.429, 0.424)	82	3290	---
A) WOLED with LIG (FF = 36%)	3.5	113	101	(0.418, 0.416)	81	3445	1.19x
B) WOLED with LIG (FF = 69%)	3.6	108	93	(0.423, 0.421)	82	3385	1.09x

Table 9: Summary of the White PHOLED devices on LIG substrates

LIG was deposited and patterned uniformly across a 15cm x 15cm substrate. The patterned substrate can be seen in Figure 14, where the yellow area is the emissive area and the gray area is the non-emissive LIG. The fill factor is approximately 70%. A white PHOLED device was grown on the substrate and the substrate was separated into 5cm x 5cm panels for testing. When the panels were tested, there was high leakage in the panels caused by the sharp LIG profile. The efficacy result from the panels with the LIG were 50 lm/W, while the reference panel was 60 lm/W.

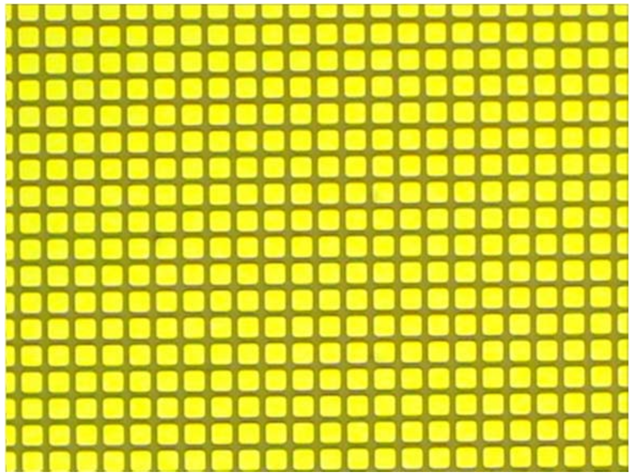


Figure 14: A picture of the patterned LIG substrate. The yellow area is the emissive area and the gray area is the non-emissive LIG.

It is uncertain at this time that LIG is an effective scalable method for efficacy enhancement. Although the LIG does provide efficacy enhancement, there are several key issues that would need to be overcome before this approach could be transferred to manufacturing. Issues include minimizing leakage currents and overcoming the reduced emissive area. The scalability of the LIG to large area lighting panels is yet to be proven.

I. Phase 4 – Luminaire Fabrication

Once the final designs were complete, the solid models of each of the components were drawn and sent out for 3D printing. See Figures 15 through 18. These models were used to evaluate the current mounting method and ensure that they fit together and are easily assembled.

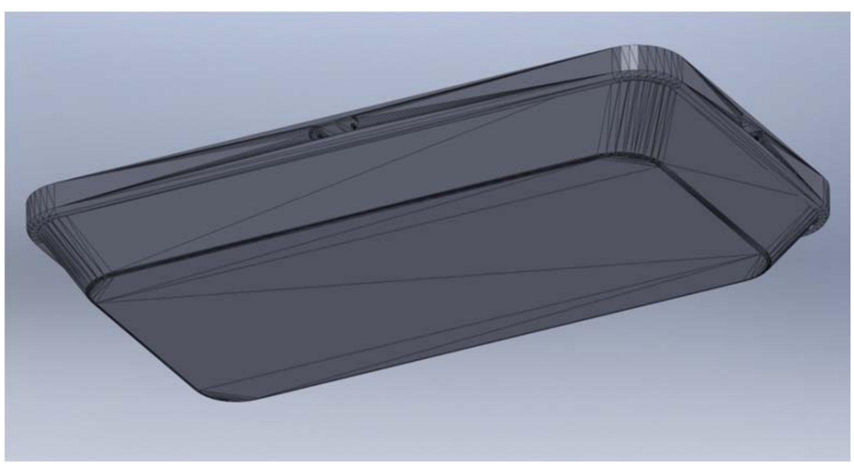


Figure 15: Solid model of the lighting module which will include OLED lighting panel, lens and fixturing.

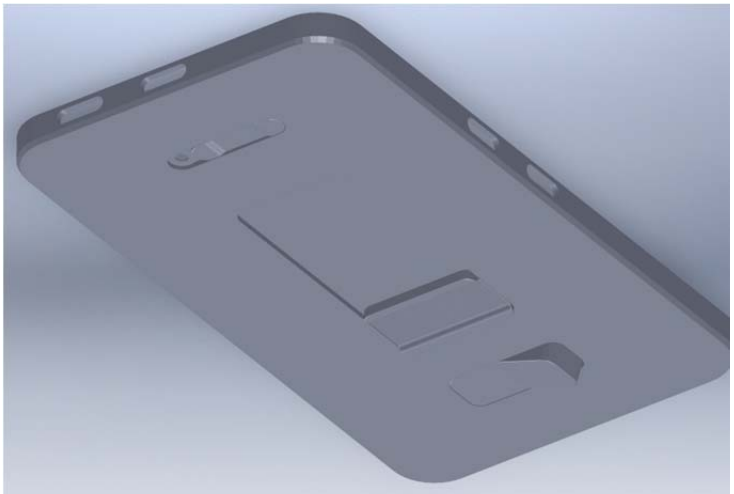


Figure 16: Solid model of the power supply. The power supply will include an on/off switch, and a slide for dimming.

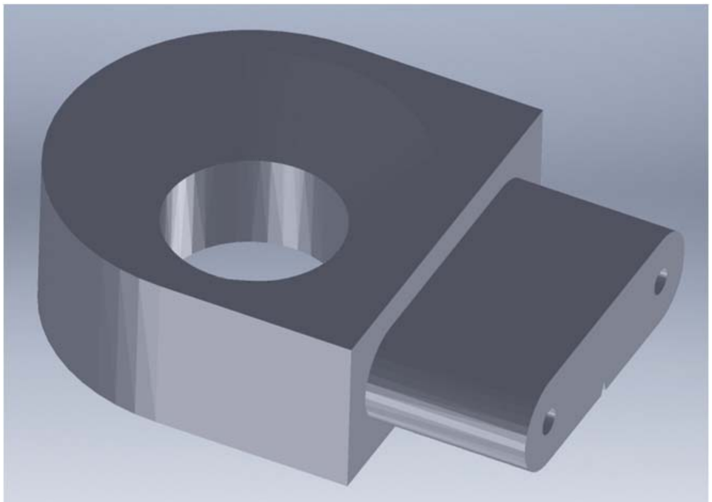


Figure 17: Solid Model of the mounting plug. This plug will be inserted into the unused power slots in the power supply module and the lighting module. Once inserted, the hole in the plug will be used for a screw to mount the module.

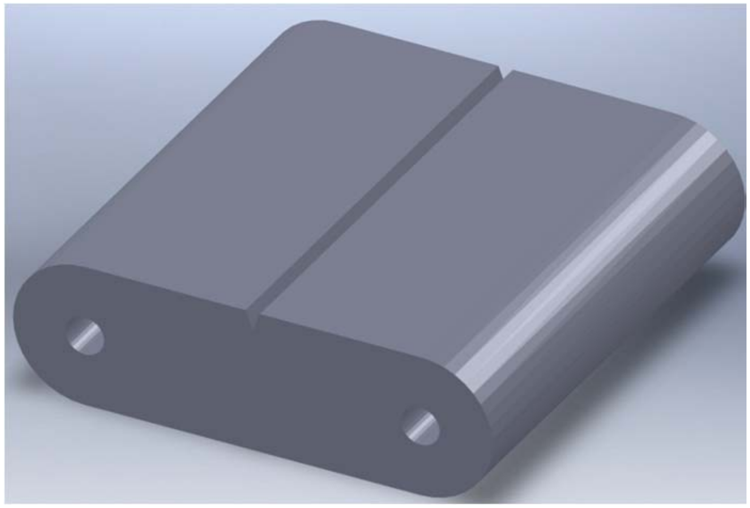


Figure 18: Solid model of the electrical plug. This plug will be used to connect to modules together and provide power from one module to the other.

The 3D printed parts are shown in Figure 19. The lighting module was printed in the final overall size. Although the lighting module will include several components; an OLED lighting panel, the lens and the fixturing, this model included all of them as one piece.

During the inspection of the module and mounting plugs, it was found that the tolerances used for the mounting plug and the power slots holes in the lighting module were too tight. The mounting plugs could not be inserted into the power slots. The mounting plugs will be redesigned and printed again, along with the separate components of the lighting module.

Figure 19: 3D printed model of the lighting module and mounting plug. The lighting module included the following components; OLED lighting panel, lens and fixturing, and the mounting plug.

Both parallel and series circuits were considered for connecting the light modules. Both connection types have their pros and cons, as outlined below.

For the parallel connection approach: the electrical power would require two levels of power conversion, from 120VAC to an intermediate DC voltage (e.g., 24V), and then provide a second level of power conversion from 24VDC to a constant current. We expect that we could achieve 90% efficiency for conversion from 120VAC to 24VDC and between 90% to 95% efficiency converting from 24V to the constant current. So the overall conversion efficiency from the wall outlet to the lighting panel would only be slightly above 80%, which would not meet our performance objectives. However, the parallel circuit design will allow the lighting modules to be configured into any layout using 1 to 10 lighting modules, which would be ideal for any product.

For the series connection approach: The electrical power would only need one level of power conversion, from 120VAC to a DC voltage to operate 10 modules. It is expected that we could achieve at least 90% efficiency for conversion from 120VAC to the required DC voltage. However, the series connection would limit the flexibility of the lighting panel layout such that 10 lighting modules would need to be connected in a single string. This is the approach that was selected.

The design of the under-cabinet luminaire comprises a control module, 10 lamp modules, 10 crossovers, and one terminator. Connections between the control module and the lamp modules are made by crossovers in such a way that the lamp modules are series connected. Lamp modules have two connectors (sockets) so as to enable side by side connections. The control module has only one connector for powering the lamp modules. Crossovers are either a module connection cable or an edge connection plug and may be used interchangeably. The crossover cable and edge connection plugs will be custom made components. Figure 20 show a, simplified schematic of how these elements interconnect. The plugs and sockets for the interconnection are polarized so that they can be inserted only in one way.

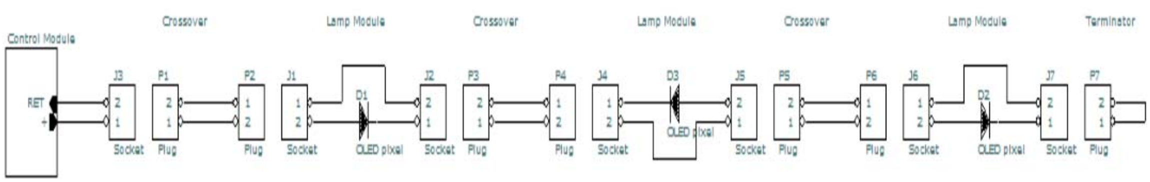


Figure 20: Simplified Schematic for Lighting Module Connection

We selected PlasticsOne to manufacture the connectors. With their help, we have defined the requirements for the edge connector that requires a custom plastic molding but can use a modified form of one of their standard pins. This will reduce the cost of the connector. The edge connector electrically connects two lighting modules that are adjacent to each other. The edge connector has been designed ordered along with the lamp modules interconnection cable that will be used when the lamp modules are not mounted adjacent to each other.

As we continued to develop the power supply for the luminaire, it was found that some of the electrical components, mainly the inductors, were going to be fairly large. This resulted in increasing the size of the control, in both area and thickness. Since the increase in size of the control module was not desirable, it was decided to locate the power supply at the AC plug location, similar to the plug in power supplies that are used for many of the electronic devices today. Now the large electrical components will no longer need to be located in the control module, thus reducing its size. Included in the control module is an on/off switch and a slider for dimming. Figure 21 shows the components of the control module and the power supply mounted into the plug.

Figure 21: Picture of the control module and power supply; from left to right: Bottom piece of the control module with holes for mounting; back side of the control module top; assembled control module with the power switch and the slide for dimming; power supply printed circuit board mounted inside the AC plug assembly; assembled AC plug.

The lens is made from acrylic and has a pocket machined into the back to hold the OLED lamp. See Figure 22. Two small notches are machine into the edge of the lens for mounting the jacks for the power plug. The bottom piece of the lamp module, the mounting plate, is designed to hold the module circuit board that connects power to the lamp module. Additionally, the mounting plate has holes for mounting the module under the cabinet. An aluminum frame is designed to go over the lens and hold it tightly to the mounting plate by using screws in the corners. Figure 23 shows the components assembled.

The module circuit board, shown in Figure 24, uses spring contacts to make the electrical connection to the 15 pixels on lighting panel. Since all the pixels on each lighting panel are in a parallel circuit, a single fuse is designed to be in series to each spring contact, such that a short in an individual panel will cause the fuse to blow, only turning off the bad pixel, with the remaining pixels staying illuminated.

A concept deliverable is shown in Figure 25. It consists of 10 lamp modules, a lamp control module, a power supply and several connectors to connect the lamp modules together. The power supply is designed to be plugged into a standard wall outlet and will connect to the control module using a 5 foot cord. The control module has an on/off switch and a slide that can be used for dimming the OLED lamps. The ten lamp modules are connected in a continuous string using several different types of plugs. There are two sided plugs that allow the lamps to be adjacent to each other and plugs on the end of a wire to allow the modules to be spread out. This method of light module connection allows for flexibility in the layout.

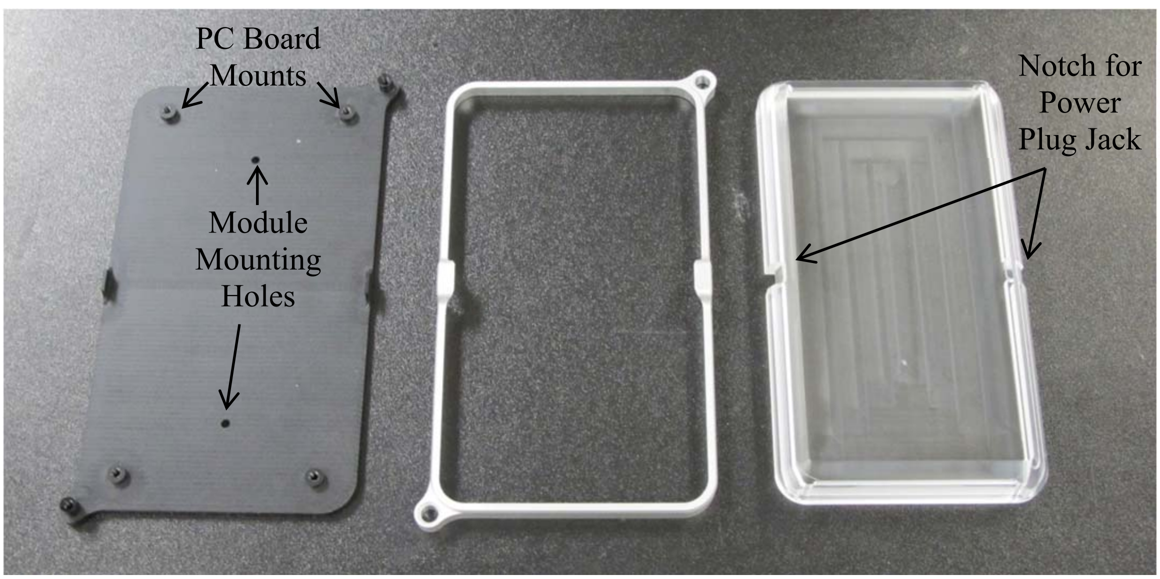


Figure 22: Picture of the lamp module components; from left to right: mounting plate; aluminum frame; lens.

Figure 23: Picture of the assembled lamp module without the OLED lighting panel.

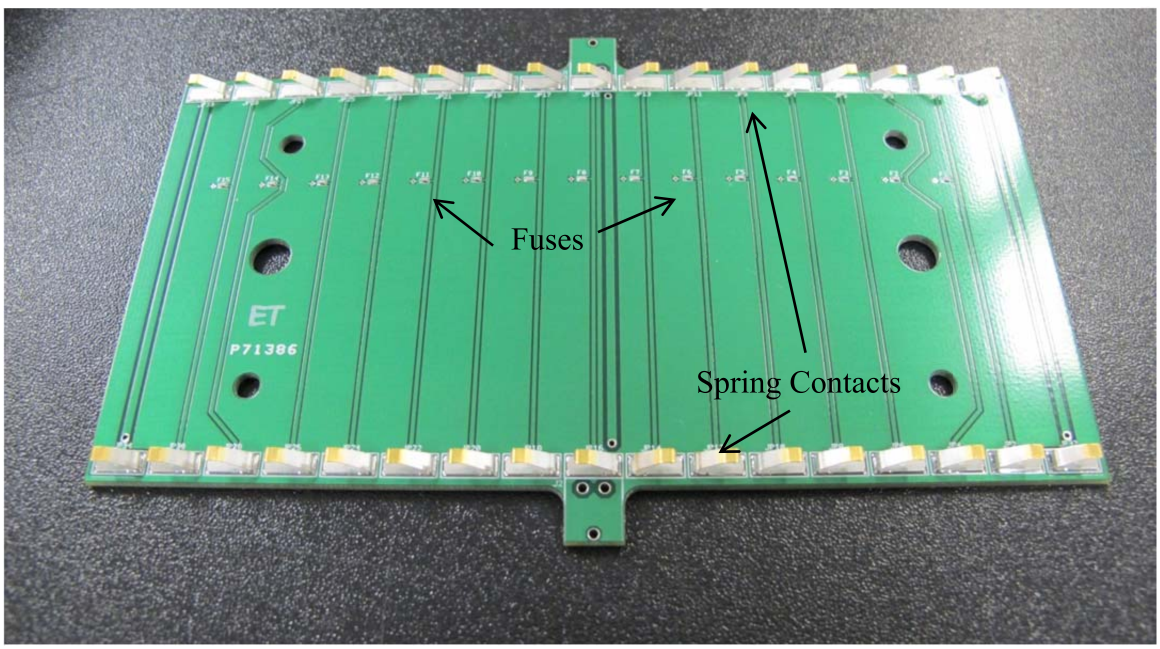


Figure 24: Picture of the lighting module circuit board

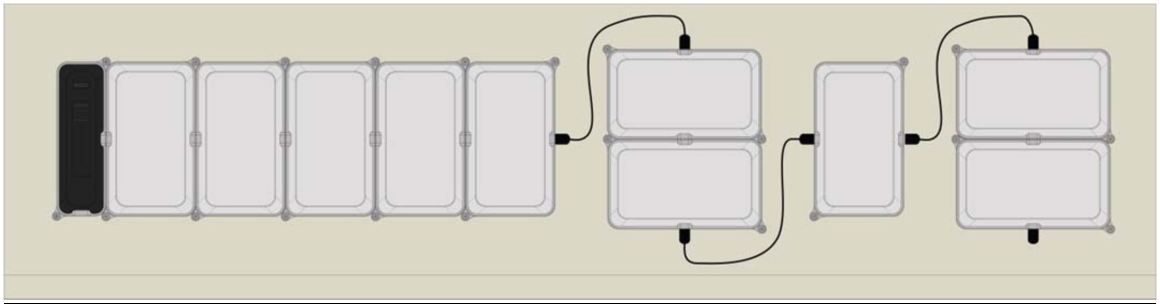


Figure 25: Final concept drawing of the deliverable. Each deliverable will consist of the power supply (not shown), the control module (left) and 10 OLED light modules that will be connected in a single string. Different types of connectors will be supplied allowing flexibility in the layout.

In Month 24, we reported that we had developed two phosphorescent OLED under-cabinet lighting systems, marking the completion of Milestone 5. The under-cabinet lighting system is shown in Figure 26.

Figure 26: OLED under-cabinet lighting system. Each under-cabinet lighting system is comprised of ten 15cm x 7.5cm lighting modules mounted in outcoupling enhancement lenses and a control module.

The lamps are connected together using either plugs or wires with plugs on each end, allowing for unlimited configurations. The lamps are driven by an OLED driver mounted in an enclosure which includes the AC plug. The drive electronics efficiency was measured at 91% at full brightness.

Due to the large size of the lighting system, we could only predict its efficacy by characterizing an individual lighting module. Results are shown in Table 10, and for our high efficiency configuration we have achieved a combined power supply and lamp efficacy of 56 lm/W. These results are for 42 lumen output per panel, representing 420 lumens per lighting system.

Panel 15 cm x 7.5 cm	**At 1,000 cd/m^2 (19 lumens)**	**At 2,200 cd/m^2 (42 lumens)**
Efficacy [lm/W]	70	61
Driver Efficiency [%]	91	91
Overall Efficacy [lm/W]	64	56
CRI	85	85
Luminous Emittance [lm/m^2]	1,700	3,750
Voltage [V]	3.8	4.1
1931 CIE	(0.446, 0.427)	(0.449, 0.427)
Duv	0.008	0.007
CCT [K]	3,030	2,990

Table 10: Single lighting module performance parameters

The metrics we set for this program were extremely aggressive. The performance we achieved and report here represents a very significant advancement.

J. Commercialization

In this project UDC has successfully developed and demonstrated an under counter lighting system, incorporating our energy efficient phosphorescent OLED technology. We met the program goals and delivered an under-cabinet lighting system that produced 420 lumens at an overall efficacy of 56 lm/W. Our program deliverables clearly show the importance and value of OLED lighting. We selected under cabinet lighting as an ideal first entry product opportunity to launch OLED lighting for residential applications. OLED lighting offers a very thin, high quality light source which is both energy efficient and operates at low operating temperatures, making it ideal for kitchen applications where food is present.

Consumer's desire for the best lighting environment is another trend that will drive market growth of OLED lighting. In addition to the reduced glare, increased uniformity, multiple light distributions, and enhanced visual interest & design flexibility benefits of OLED, the visual quality of light is characterized by color temperature and color rendering index (CRI). Because OLEDs are self-emissive and can be designed to produce a more complete spectrum of wavelengths, they produce a more natural light. Studies have shown that more natural lighting is appealing and desirable to lighting customers. The desire for quality light is a key driver for the OLED lighting market. Additionally, the OLED form factor permits luminaires that are lightweight and can be produced in exciting and innovative forms.

We believe that the work performed under this program accelerates the use of OLEDs as an energy saving form of solid state lighting. The largest energy savings would come from replacing incandescent lighting in the residential market, and fluorescent lighting in the commercial sector. Assuming we realize commercial lighting products offering 120 lm/W by 2017/18, we see an energy savings potential of 0.22 quads, representing 3.7 million metric tons of carbon (MMTC).

To further articulate the value proposition, performance benefits include increased energy savings over other light source technologies, including LEDs, higher levels of sustainability, and improved lighting quality. The lightness of OLEDs provides design flexibility, reduces the material requirements in the luminaire construction, and reduces additional environmental impacts by lowering transportation costs. Consistent with sustainability trends in the building industry, OLEDs do not contain hazardous materials, such as mercury. This mitigates the need for OLEDs to be disposed of as hazardous materials like the incumbent fluorescent technology.

Today OLED lighting is still in its infancy. Various manufacturers have established pilot OLED lighting panel manufacturing lines. As a result, over the next couple of years we expect see an increasing quantity of OLED lighting panels available for luminaire manufacturers to produce quantities (thousands or tens of thousands) OLED fixtures. This will enable the market to experience the value of OLED lighting and understand its characteristics.

As a consequence of the initial low manufacturing volumes, OLEDs over the next couple of years will be more costly than the fluorescent counterparts they will replace. Therefore, we currently need to develop OLED lighting targeted toward high-end applications (such as under-cabinet lighting), where early adopter customers will be more receptive to trading the higher cost for higher performance luminaires and improved quality light. We also anticipate that as the lumen output and luminance per m^2 increases, this will reduce the cost of OLED lighting and encourage wider acceptance.

Value Proposition for OLED Lighting

Increased energy savings:
Given the projections for increased OLED efficacy, by 2015 OLED luminaire performance will be on par with the incumbent fluorescent technology. In comparing OLED to LED and considering driver, thermal optical conversion, OLED efficacy will be on par or higher than that of LED in 2015. OLED efficacy will be even higher compared to flat-panel LED. Ultimately, OLED lighting will create the largest energy savings.

Higher levels of sustainability:
OLED luminaires not only eliminate hazardous material but also embed less energy in the manufacturing and transportation processes. The thinness and minimal weight of the OLEDs themselves facilitate the use of lighter and innovative materials in the luminaire construction. See Figure 27 for a comparison of luminaire construction for various lighting elements.

Improved light quality:
OLED lighting provides quality benefits that are not possible using fluorescent or even LED lighting for general lighting in commercial applications. Improved visual quality is a result of several intrinsic characteristics of OLEDs. First, OLEDs are low brightness and are actually visually pleasing to view directly. To provide a frame of reference, new thin outcoupling technology is being developed that will enable OLED lighting panels to have high efficacy and so competitively produce light at 6,000 – 10,000 lm/m^2, enabling on OLED fixture to provide close to an equivalent amount of light as a fluorescent lighting fixture of similar area. Luminaires using these fluorescent lamps require shielding or diffusion to prevent a direct view of the lamp. Glare control is even more critical for LEDs. OLEDs, on the contrary, are thin and visually comfortable. Given their unique form, tremendous design flexibility is an inevitable result, thereby creating the possibility of new and innovative luminaires, lighting design approaches, and architectural integration. Second, using PHOLED technology, we will create luminaires with superior color attributes, including CRI.

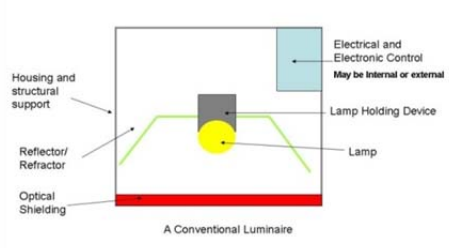
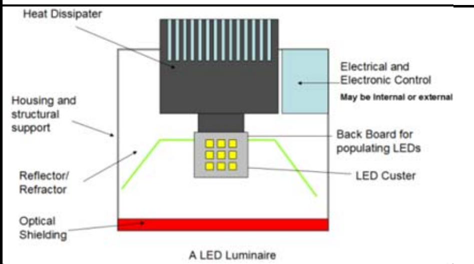
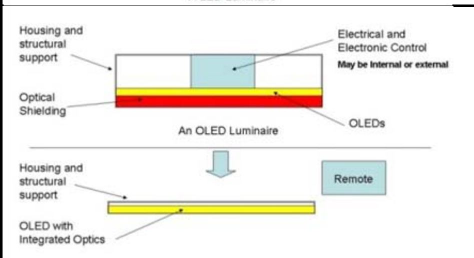
Source	Luminaire Construction	Description
Fluorescent		The luminaire housing is typically constructed of steel or aluminum. Optical shielding devices are usually either acrylic or metal. The fluorescent lamp contains mercury.
LED		While LEDs do not contain mercury, the amount of metal material required for heat sinking often makes an LED luminaire more material-intensive than its fluorescent counterpart.
OLED		OLED luminaires have fewer parts and use lightweight and thin materials with an estimated reduction of over 50% in packaging and shipping costs. Installation is simplified because luminaires are light in weight and operate at low voltage.

Figure 27: Comparison of Luminaire Construction for various lighting elements

Commercialization Strategy

The customer base in the commercial lighting market is very broad, and commercial lighting installations can exist in new building construction or in renovations of existing buildings. Customers include building owners, building operators, facility managers, and numerous other entities. To ensure that the lighting installation meets these customers' needs, professionals such as architects, engineers, and lighting designers are often employed to assist in developing the correct lighting specification. For example Acuity Brands Lighting (ABL) is the largest manufacturer of lighting equipment in the US with the experience to develop and bring to market luminaires and lighting systems that meet the needs of this multi-faceted customer base. Acuity Brands Lighting already has in place several sales channels to serve this complex set of customers.

The procurement and purchase of the lighting equipment is often enabled by wholesale and retailers such as electrical distributors (who often work with independent lighting sales agents) as well as home centers. Even the installers of the lighting equipment, such as general and electrical contractors, play a role in the specification of lighting fixtures and controls, and this trend is increasingly prevalent as design-build contracting firms and larger energy service companies (ESCOs) increase their presence in the lighting market.

The end user demand created by companies like ABL, WAC lighting and others will drive accelerated adoption of the PHOLED panel technology. The accelerated adoption will drive accelerated manufacture of the PHOLED panel technology by companies like Moser Baer Technologies. These positive interactions between the end-user market channels, and the manufacturing market channels, will accelerate the whole market of OLED technology and help achieve the DOE SSL price targets.

UDC has business relationships with panel manufacturers like Showa Denko, Moser Baer Technologies, Konica Minolta as well as relationships with lighting manufacturers like ABL. These relationships provide the channel to market for the PHOLED panel technology developed in this SSL program.

Performance Roadmaps

To have the biggest impact, we focus on panel performance used for general lighting in office, bank, retail, hospital / healthcare, public and other non-residential building types. Investment in this effort will accelerate OLED market penetration as projected below in Figure 28, as provided by Acuity Brands Lighting.

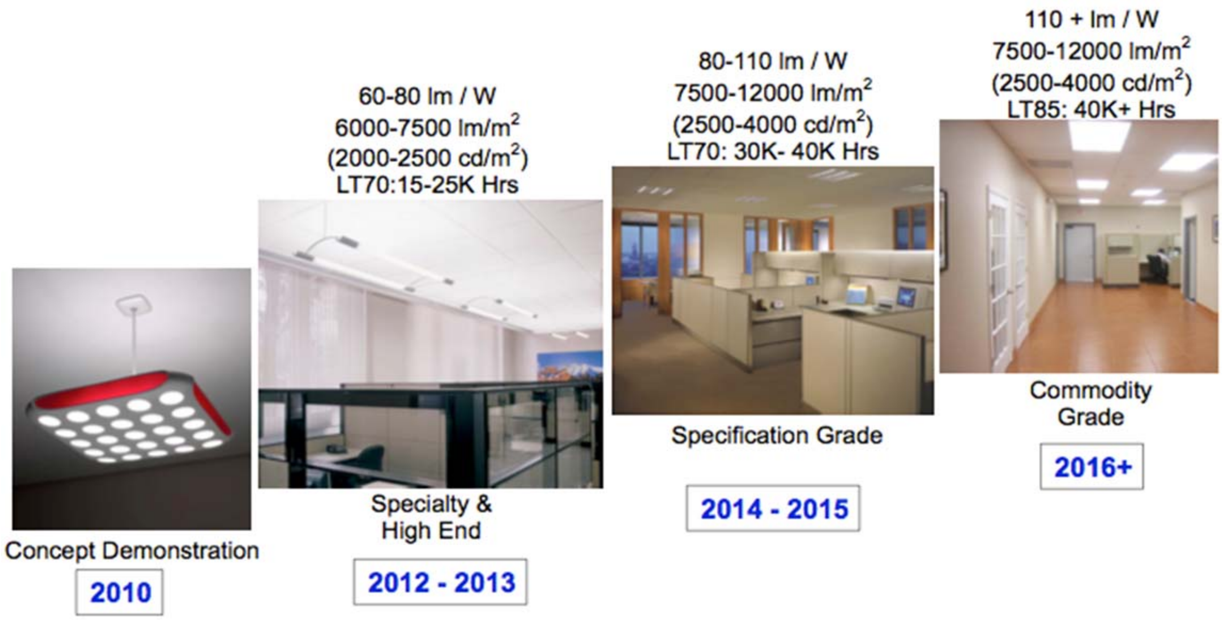


Figure 28: OLED Market Segment Requirements and Projections

Initially, we know that OLEDs will be more costly than the fluorescent counterparts they will replace. Therefore, the development of increased panel performance that will target the high-end applications where early adopter customers will be more receptive to trading the higher cost for higher performance luminaires and better quality light will be required. It is also anticipated that as the lumen output and luminance per m^2 increases, this will reduce the cost of OLED lighting and encourage wider acceptance.

Under-cabinet lighting is an ideal focus for early entry product launch. The form factor, energy efficiency and low operating temperatures make PHOLED lighting ideal for these applications. Table 11 shows a performance comparison between the PHOLED under-cabinet lighting developed under this SSL program and commercial LED under-cabinet luminaires. The data for the LED luminaires is from the Energy Star website (http://www.energystar.gov/index.cfm?fuseaction=ssl.display_products_com_pdf). The performance of the PHOLED under-cabinet lighting system made under this SSL program is very similar to the current commercially available LED under-cabinet lighting systems which makes this an ideal initial application for OLED lighting systems.

Manufacturer	Model	Efficacy (lm/W)	Wattage	Light Output	Color Temp	Features
UDC		**52**	**10.96**	**570**	**2940**	**Dimmable**
Philips Solid-State Lighting Solutions, Inc	523-000027 -49	47.5	10.09	479.3	3000	Dimmable
Philips Solid-State Lighting Solutions, Inc	523-000027 -50	48.68	20.32	989.2	3000	Dimmable
Philips Solid-State Lighting Solutions, Inc	523-000050 -02	43.9	22	527	2700	
Philips Solid-State Lighting Solutions, Inc	523-000050 -14	53.1	12	632	4000	
Kichler Lighting	12054	39.6	11.75	465	3000	
Greenlite Lighting Corporation	LED/UC-24	42.7	10.6	452.5	3000	
EEMA Industries Dba Liton Lighting	LKULED1608 V12-ES	26	10.8	281	3500	
Good Earth Lighting, Inc.	G0518LD-BK SS-l	45.24	7.5	338	3000	Dimmable

Data from: ENERGY STAR Qualified LED Lighting -
http://www.energystar.gov/index.cfm?fuseaction=ssl.display_products_com_pdf

Table 11: Performance comparison between the PHOLED under-cabinet lighting developed under this SSL program and commercial LED under-cabinet luminaires.

Cost

Wide-scale adoption of OLED lighting cannot be enabled without a significant cost-down effort. Clearly production volumes are closely tied to production costs, and economies of scale will need to be realized to achieve target costs of < $\$100/m^2$, required for the large scale adoption of OLED lighting. Figure 29 shows an interesting comparison/projection of OLED lighting costs as compared to LED lighting costs, showing that when OLEDs achieve these target costs, OLED luminaires can be cost competitive from LED products.

Luminaire Cost Projection – 2015

Total Variable Cost of commodity grade luminaires, 4000 lm output (to comply with anticipated future building codes)

Cost	WW Regular LED	WW LED Flat Panel	OLED with IR Loss	OLED with no IR Loss
Housing	$40	$20	$20	$20
Driver	$10	$10	$10	$10
Heat sink/Waveguide	$10	$10		
Initial lm required for 4000 lm output	5000 lm (80%eff)	6060 lm (66% eff)	4762 lm (84% eff)	4762lm (84%)
LED or OLED source cost	LED cost $16.5	LED cost $20	OLED cost $ 43	OLED cost $43
Total Luminaire cost	$76.5	$60	$73	$73
Wattage consumption	27W @ 184 lm/W	33W @ 184 lm/W	29 W @162 lm/W	26 W@180 lm/W
Add. Elec. for 40K Hrs operation, $0.1/kWHr	+$4	+ $28	$12	0
Cost Ratio of OLED /luminaire	22%	33%	59%	59%

- LED cost target: $3.3/Klm for WW LEDs in 2015 (DOE MYPP'10, p.69) OLED cost target: $90/m^2, $9/Klm in 2015 (DOE SSL Manufacturing Roadmap'10, p.38)
- The simplicity of OLED luminaires offsets the higher cost of panels.
- Higher portion of "lamp" cost more easily justify investment into OLED manufacturing.

** Peter Ngai, DOE SSL Manufacturing and R&D Workshop, San Jose, CA, Apr 2010.*

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Figure 29: OLED Cost Comparisons with LED Products

More specifically, the cost for a PHOLED under-cabinet product can be estimated by using a few assumptions. It is expected that by 2015, the cost for a OLED panel will be approximately $250/m^2. It is estimated that 0.1 m^2 will be required for an under-cabinet luminaire, making the cost of the OLED $25. Assuming that the fixture cost is equal to double the OLED panel cost, the total cost of the luminaire would be $75. Typically the retail cost of an item is double the cost, thus make the retail cost of the OLED luminaire $150. This cost is comparable with the cost for similar performance LED under-cabinet lighting systems that are listed in Table 12.

Brand	Model	Efficacy (lm/W)	Light Output	# of LEDs	Size (inch)	Retail Cost	$/linear Inch	lm/$
Philips	523-000027-04	47.5	479.3	10	19.3	$135	7.00	3.55
Philips	523-000027-05	48.68	989.2	20	39.3	$225	5.73	4.44
Crescent	LLP8W	49.14	634	N/A	24	$150	6.25	4.23
Kichler Lighting	12054	39.6	465	4	30	$200	6.67	2.32

Table 12: Cost for LED under-cabinet lighting systems with similar performance to the PHOLED system developed under this SSL program.

K. Conclusion

During this 2 year program, we further developed our high efficiency white Phosphorescent OLEDs from the first milestone, achieving a 80 lm/W single pixel to the final milestone, achieving an under-cabinet PHOLED lighting system that operates at 56 lm/W at 420 lumens. Each luminaire was comprised of ten 15cm x 7.5cm lighting modules mounted in outcoupling enhancement lenses and a control module. The lamps modules are connected together using either plugs or wires with plugs on each end, allowing for unlimited configurations. The lamps are driven by an OLED driver mounted in an enclosure which includes the AC plug.

As a result of advancements gained under this program, the path to move OLED lighting panels from development into manufacturing has been further realized. We have found that under-cabinet lighting is an ideal first entry product opportunity to launch OLED lighting for residential applications. From the studies that we have performed, our PHOLED under-cabinet lighting system performance is very similar to many of the current commercially available LED under-cabinet luminaires. We also found that the projected cost of PHOLED luminaire should be comparable to the LED luminaire by 2015. With the additional benefits of PHOLED lighting, no glare, better uniformity and low operating temperature, it can be easily seen how the PHOLED under-cabinet luminaire could be preferred over the LED competition.

Although the metrics we set for this program were extremely aggressive, the performance we achieved and reported, represents a very significant advancement in the OLED lighting industry.