Final Scientific/Technical Report

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OLED Luminaire with Panel Integrated Drivers and Advanced Controls

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A. Executive Summary

For this DOE award, Acuity Brands Lighting developed a novel OLED luminaire system featuring panel-integrated drivers at each individual OLED panel. The luminaire has a base station that receives user commands and performs AC/DC conversion. A power line communication (PLC) protocol is used to provide both power and digital control to each panel. A 66-panel Canvis™ luminaire using state-of-art OLED panels based on this system was successfully constructed. This is a first demonstration of such a luminaire architecture. It is also the first known implementation of this number of independently addressable nodes with a PLC protocol. This luminaire system architecture has added benefits in the flexibility of using multiple panel vendors for a given product, forward compatibility with future panels, and reduced luminaire wiring complexity and assembly time.

B. Accomplishments vs. Goals and Objectives

The original project proposal was to develop an OLED luminaire system where the panels were driven by integrated drivers that drew power from a low voltage DC rail. The integrated drivers were to perform DC current modulation while the low voltage power was to be provided by a base station that performed AC/DC conversion (Figure 1). Further, a key objective of this project was to explore different dimming schemes including global dimming where all panels were dimmed together, and more ambitiously, where the panels were individually addressable.

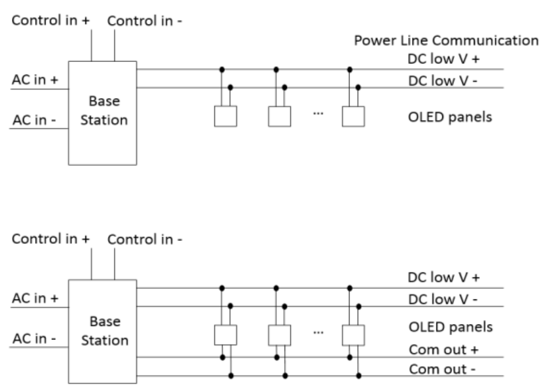


Figure 1. Top: a system with power line communication between the base station which performs AC/DC conversion and the OLED panels with integrated driver; Bottom: a similar system with fixed wire instead of power line communication. Note that the Control signal can be either a 0-10V digital dimming signal or a DMX signal. The communication between the base station and the OLED panels can be either one-to-many or individually addressable.

The proposed luminaire deliverable was to have the following performance characteristics:

Table 1. Proposed panel and luminaire specifications

Panel CCT	3000K (3500/4000K optional)
Panel Luminance	2500-3000 cd/m^2
Panel CRI	>85
Panel Lifetime (L_{70})	>25,000 hrs.
Panel Efficacy	80 lm/W

Total Luminous Output	4000-5000 lm
Luminaire Efficacy	65 lm/W
Luminaire Control (option 1)	0-10V dimming, global
Luminaire Control (option 2)	DMX or other protocols, individual panel addressable

Again, dimming method other than by additional signal wires was considered a "stretch goal", as was individually addressable panels. The OLED panels were to be provided by OLEDWorks LLC with a panel efficacy goal of 77 lm/W at a luminance of 3000 cd/m^2.

At the conclusion of the project, a full-size, 66-panel Canvis using the developed driver architecture was constructed. Relevant characteristics are listed below.

Table 2. Achieved panel and luminaire characterisitics

Panel CCT	2700K
Panel Luminance	2900 cd/m^2
Panel CRI	89
Panel Lifetime (L_{70})	40,000 hrs.
Panel Efficacy	86 lm/W
Total Luminous Output	4871 lm
Luminaire Efficacy	49.3 lm/W
Luminaire Control	DMX/RDM interface, PLC protocol, all panels individually addressable

A few explanatory notes:

- The most efficacious, then commercially available OLED panels from LG Display was used to constructed the luminaire. 2700K panels using a 3-stack design was the most efficacious type available.
- OLEDWorks provided panels with an average efficacy of 64 lm/W and maximum efficacy of 74 lm/W at 3000K. OLEDWorks panels were used to demonstrate cross-vendor compatibility that this system enables.
- The stretch goal of individually address each panel while minimizing wiring complexity by applying PLC was accomplished.
- The panel-integrated driver was not optimized in power, which led to lower luminaire efficacy than projected. The panel drivers operated at 72% and an 88% efficient power supply was used for AD/DC conversion.
    - In a conventional luminaire design, at 85% for combined optical and driver efficiency will result in a luminaire efficacy of **73 lm/W** with 86 lm/W panels.
    - There is room for improvement in the panel driver for at least 10%. Further improvement can come from more precise control of the rail voltage.
    - Additional luminaire design considerations, such as addressing a cluster of panels rather than each individual panel can further reduce the overhead from the added communication layer.

C. Project Activities

C.1. Luminaire Mechanical Design

The key activity that took place in the course of this project was the new cassette design (Figures. 2 and 3) that holds the panel driver at the back of the cassette, away from the OLED panel. In previous designs, integrated electronics are in direct contact with the back of the OLED panel, giving rise to possible thermal complications. The new cassette design was compatible with cassette holders already in use at Acuity for the current Canvis and Trilia OLED luminaires.

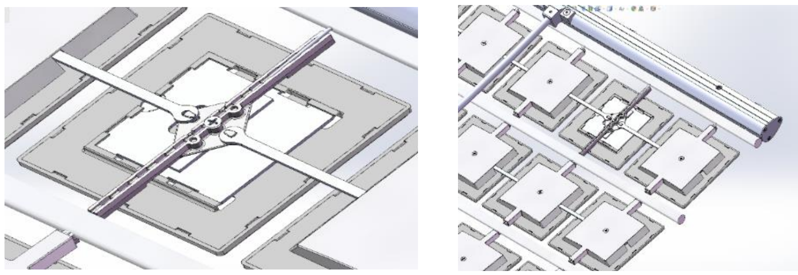


Figure 2. Cassette and connection system in the Canvis luminaire.

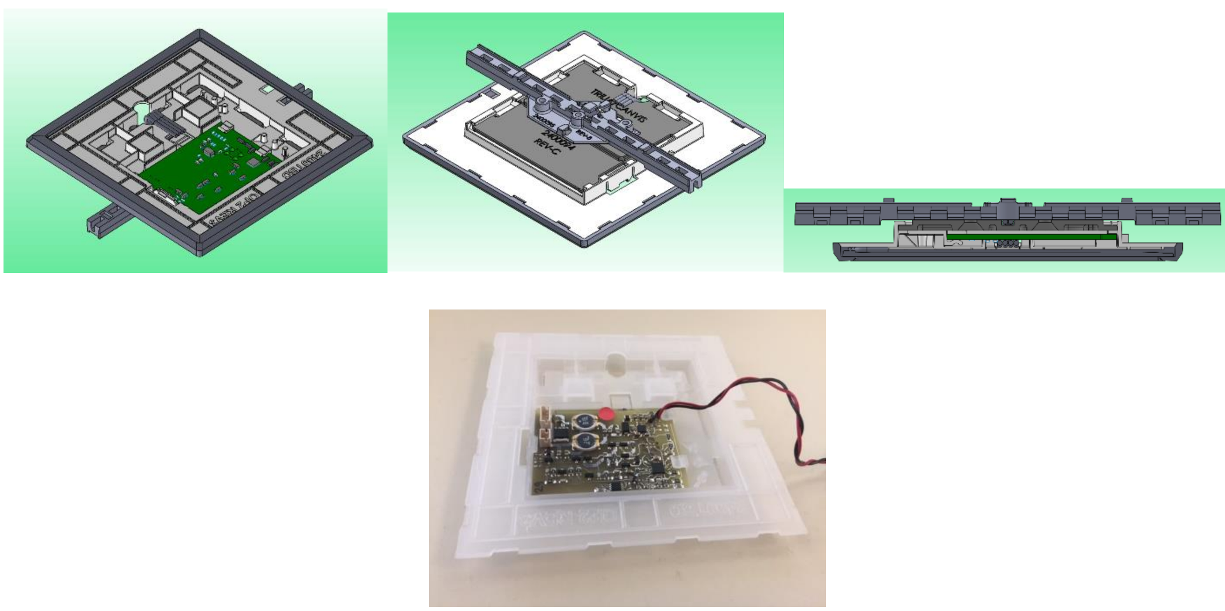


Figure 3. New cassette to house the panel driver. Note the added thickness in the back to accommodate the driver.

C.2 Base station, panel driver design and associated communication protocol and firmware

This section comprises the bulk of the technical achievement achieved in this project. The final implemented system architecture is shown in Figure 4. The base station provides AD/DC conversion and user interface as originally planned. During the course of development, it was determined that a strand controller is necessary giving the large number of independent panels. Robust PLC communication over a serial string up to 17 panels were demonstrated. However, since the full-size Canvis contains 6x11 OLED panels, an intermediate strand controller was needed. The strand controller has 6 outputs and each output drives 11 panels in series.

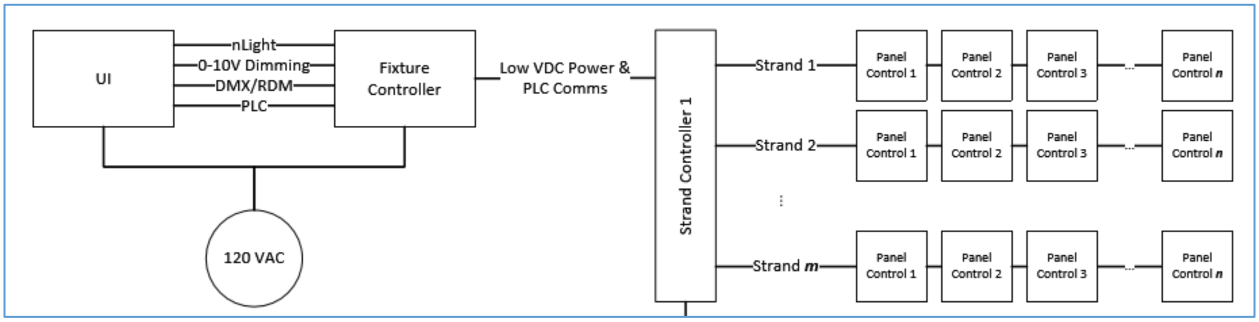


Figure 4. Multiple iteration of hardware for the base station, strand controller and panel driver

Several iterations of the base station and panel driver hardware were carried out and brought up (Figure 5). The PLC protocol is bi-directional with a data rate of 250 kb/s. 16-bit addressing was used which meant the system could have up to over 3000 nodes theoretically.

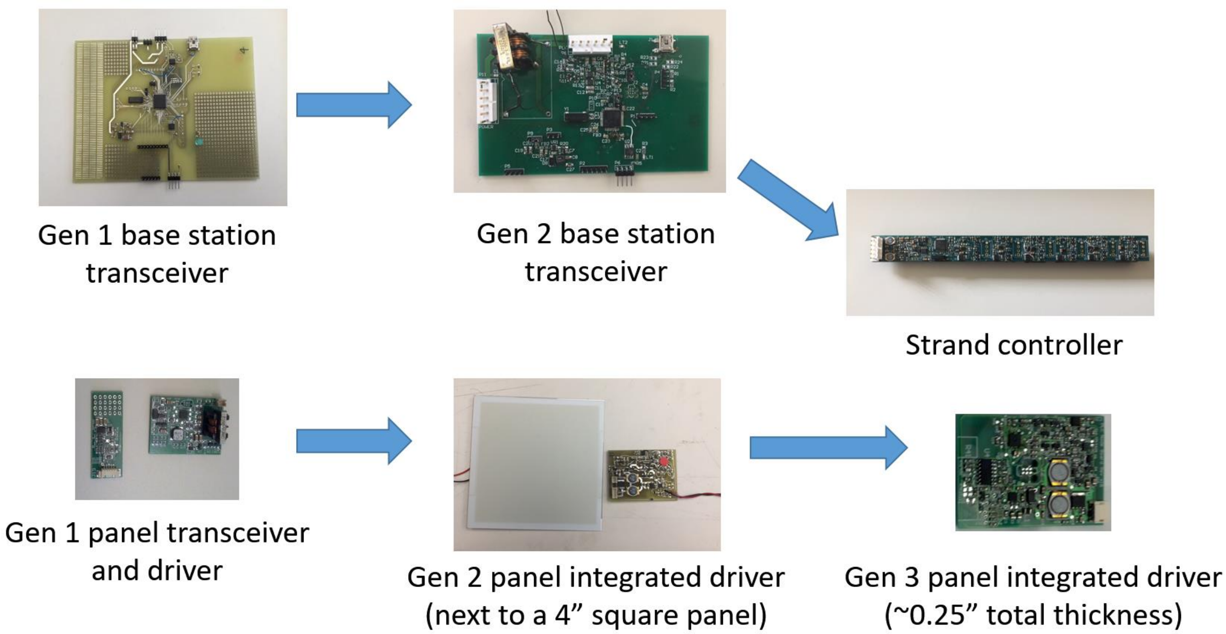


Figure 5. Multiple iteration of hardware for the base station, strand controller and panel driver

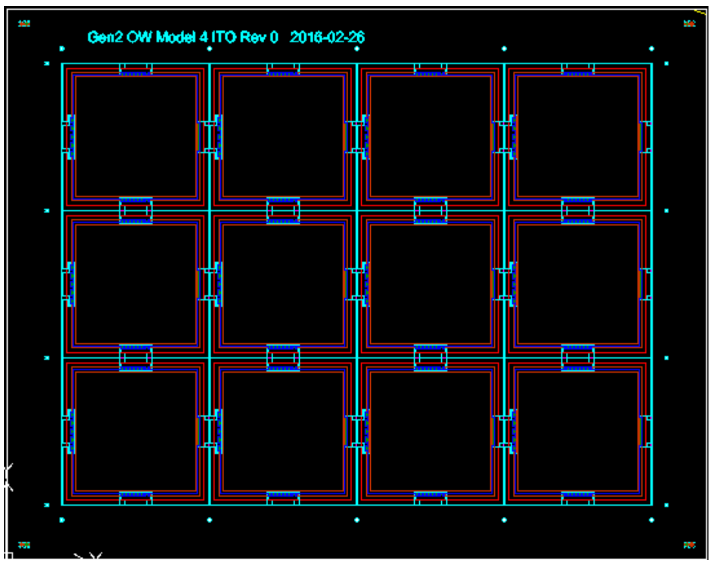
C.3 OLED Panel Development at OLEDWorks

OLEDWorks and ABL discussed and agreed upon panel specifications for this project. The target panel specifications are shown in the table below:

Format	Square
Panel size (mm)	99x99
Panel Thickness (mm)	1.5
Emitting Area (mm)	80.65x80.65
Emitting Area (cm2)	65
Estimated uniformity (3-stack)	80%

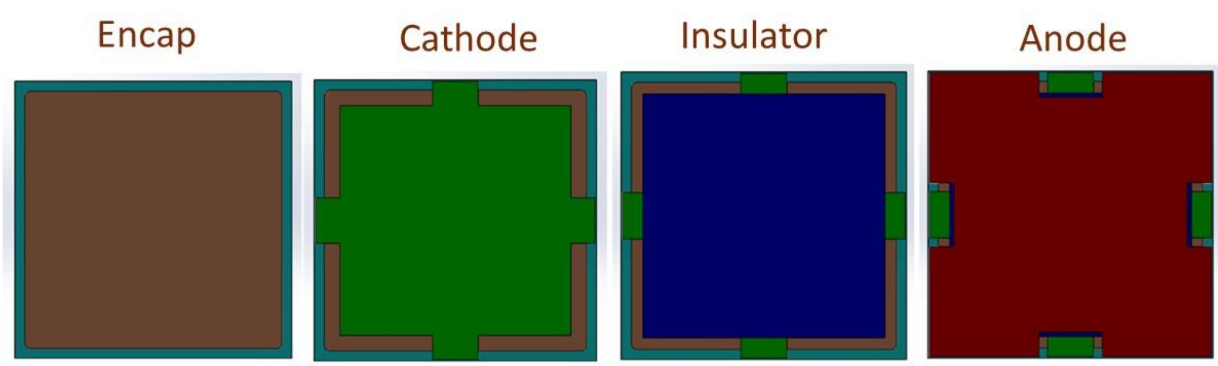
Encapsulation	TF/face seal
Brightness (cd/m2)	3000
Drive Voltage (V)	8.2
Efficacy (lm/W)	77
Flux per panel (lumens)	60

A new panel was designed for this project with dimensions of 99x99mm. The design included new encapsulation technology and 4-sided anode and cathode connections. This panel was designed on a Gen2 size substrate (370x470mm) in a 12-up array as pictured below. Integrated light extraction substrates were ordered in April and received in late May 2016. The integrated substrate technology leveraged for this project was developed in another DOE project aimed at developing high performance OLED technology (DE-EE0006701).

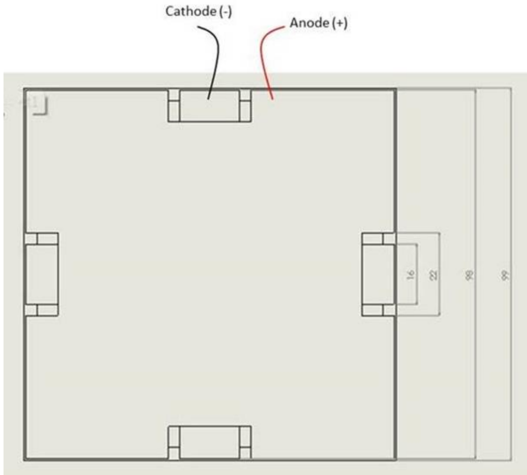


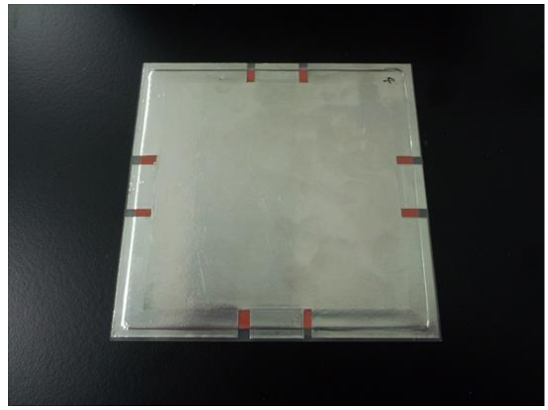
Develop panel contact method

OLEDWorks developed several new electrical contact methods during this program. The panel is designed with 4-sided anode and cathode connections for best uniformity. The specific solution for this project involved laminated metal foils which will also serve as an electrical interconnect between multi-sided contact points. Multiple foils are laminated in the sequence shown below.

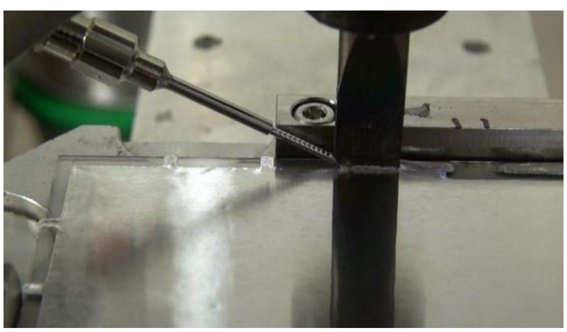


Wires can then be soldered to 2 points as shown in the diagram below (left). A rear view of an actual panel is shown in the figure below (right).



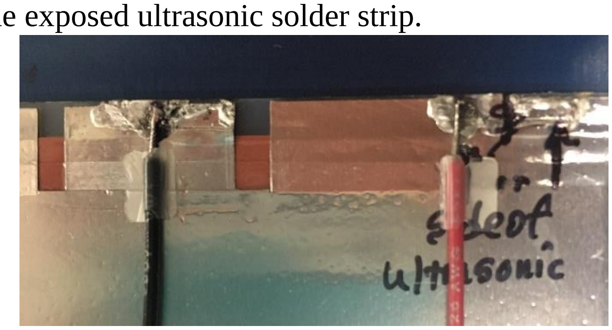


Additionally, an ultrasonic soldering method was developed in parallel as a potential low cost solution. OW had already invested in a robotic tool for applying ultrasonic solder directly onto glass or ITO/glass surface as pictured below (left). The process allows for isolated strips of solder metal to be placed on ITO, or overlapping strips of solder from a foil to the ITO as pictured below (right).



<u>Subtask 6.2 Panel testing for reliability improvement</u>

An initial batch of 12 panels was provided to ABL for initial testing. Feedback was given that voltage was not stable due to unstable contact from the electrical foil to the ITO edge contact on the panel. Improvements were made by combining ultrasonic soldering with the laminated electrical foils. Periodic notches were made along the edges of the foils to allow for a solder strip to make robust contact to the ITO as well as overlap the metal foil, as pictured below. This provided the necessary voltage stability due to improved electrical contact. Finally, flywires were soldered directly onto the exposed ultrasonic solder strip.



Initial panel performance is summarized below. Efficacy ranged from 62-75 lm/W as voltage was variable. Uniformity was above 80% on average. Color quality was slightly short of the target 85 CRI.

Data Summary at 2000 nits (1.0 mA/cm2)									
Panel	J	V	cd/m2	cd/A	CIEx	CIEy	lm/W	EQE	Uniformity
1	1.0	8.5	2047	204.7	0.419	0.392	75.8	92.9	85%
4	1.0	9.9	1946	194.6	0.419	0.396	61.7	87.5	76%
7	1.0	8.8	2006	200.6	0.418	0.394	71.7	90.3	87%

Data Summary at 3000 nits (1.5 mA/cm2)									
Panel	J	V	cd/m2	cd/A	CIEx	CIEy	lm/W	EQE	Uniformity
1	1.5	8.8	3046	203.1	0.418	0.392	72.8	92.0	84%
4	1.5	10.6	2953	196.8	0.418	0.395	58.3	88.4	73%
7	1.5	9.0	3056	203.6	0.417	0.394	70.9	91.5	87%

CCT	Duv	CRI	R9	LER
3263	-0.001	82	26	326

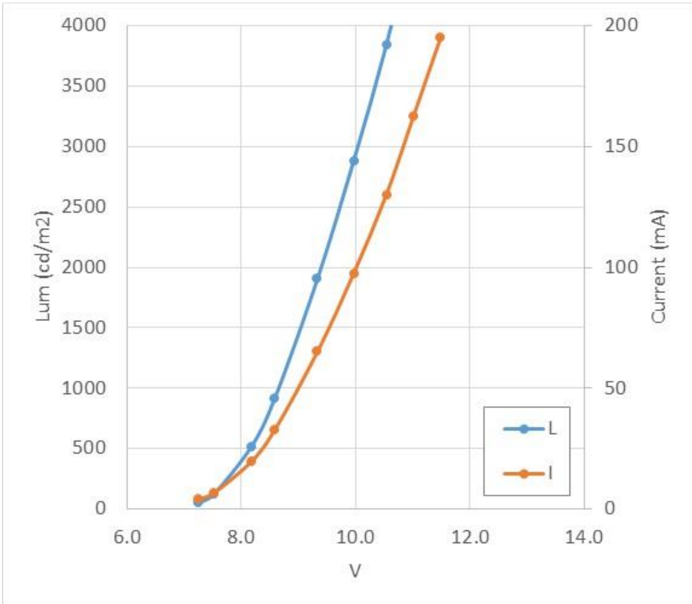
<u>Panels for final integration</u>

Several batches of integrated substrates were produced between June and September 2016, amounting to several hundred panels being fabricated and tested. All panels that passed initial testing and visual quality were then burned in for 2 weeks minimum to weed out early failures. Burn-in consisted of operating the panels at 2X nominal operating current (200 mA) in cycles of 25 min on and 5 min off. A set of panels on the burn-in tower are pictured to the right.

In the end, 85 completed panels were shipped for final integration on October 18th. Recognizing that CRI was short of the target of 85, an improved deeper red emitter was implemented. This increased the CRI from around 80 to almost 90, and R9 from 20 to over 70. This trade-off was made even though it resulted in a loss of efficacy of nearly 5 lm/W due to emission losses in the IR region. Additionally, panel voltage was higher than originally anticipated. The average voltage was 9.8V, and the average efficacy was 65 lm/W for this set of panels. Further process improvements and OLED materials were recently made that could result in a lower voltage by 1.5V, but there was not time to implement these improvements. With the voltage improvements and a more efficient narrow band red emitter, efficacy would average over 80 lm/W. The performance of this final set of panels is summarized below.

Lot	VDC	cd/m2	cd/A	CIEx	CIEy	lm/W	EQE	CIE u'	CIE v'	CCT	Duv	CRI	R9	Red Emitter
PC1-160803	9.6	3075	205.0	0.430	0.413	66.9	92.4	0.243	0.524	3200	0.005	80	25	Old Red
PC1-160815	10.0	2840	189.4	0.427	0.408	59.7	92.9	0.243	0.521	3200	0.004	86	70	New Red
PC1-160830	9.1	2910	194.0	0.425	0.409	66.9	94.1	0.241	0.521	3200	0.003	85	70	New Red
PC1-160926	9.8	3041	202.7	0.418	0.397	65.0	100.9	0.241	0.516	3300	0.000	89	80	New Red

In order to enable dimming to ~ 1%, a representative panel was characterized from very low current of 4mA up to high current of 200mA. Nominal brightness of 3000 nits is achieved at approximately 100mA, which is a current density of 1.5 mA/cm^2. The L-I-V curves are shown below.



C.4 OLEDs purchased from LG Display

In order to maximize the efficacy of the final deliverable, the most efficacious and available commercial panels were purchased from LGD and eventually was used to construct the Canvis demo luminaire. The LGD panel specifications are shown in Table 3. It should be noted that with the distributed driver design it is possible to have both both LGD and OLEDWorks panel on the same serial string as seen in Figure 6. It demonstrates flexibility of the distributed system where the luminaire can easily accommodate panels from different vendors, as well as ensuring forward compatibility.

Table 3. LGD LL055RS1-92P1-OY1 panel specifications.

Flexibility	Efficacy	Shape	Name	Size(diagonal)
				inch
Rigid	90 급	Square	SA	5.5

Model	CCT	Efficacy	Flux
	K	lm/W	lm
LL055RS1-92P1-OY1	2700 ± 150	86 ± 10	75 ± 10

Uniformity	CRI	Voltage	DC Current	LT70
%		V	mA	Hrs
>85	>85	8.6± 0.5	100	40000

Thickness	Active size	Outer size
mm	mm	mm
1.97	90x90	99x99

Figure 6. A small demo showing both LGD (top) and OLEDWorks (bottom) panels driven in the same string

D. Products Developed under this Award

The luminaire deliverable was a full-size, 66-panel Canvis capable of individual panel control (Figure 7). It is to be demonstrated at the DOE SSL R&D workshop at Long Beach, CA, Jan 31 – Feb 1. A poster on this work is to be shown at the same workshop.

Figure 7. Full size Canvis demo fixture with individual panel addressing. Two control modes are shown: scrolling text (left) and rain drop (right)

The main technology developed under this award is the base station/panel driver design as well as the PLC communication protocol and associated firmware. In addition, the cassette design was also novel. The following patent applications have been filed:

1. Min-Hao Michael Lu and Jonathan Wickus, Cassette for Holding a Planar Light Source with a Thermally Isolated Driver Board, non-provisional application,15/412,708, filed 1/23/2017
2. Jeff Scott and Michael Miu, Power Line Communication System and Auto-Addressing Protocol, provisional application, 62/452,312, filed 1/30/2017