LUMILEDS

High-Voltage LED Light Engine with Integrated Driver

Final Technical Report

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1. Executive summary

LED luminaires have seen dramatic changes in cost breakdown over the past few years. The LED component cost, which until recently was the dominant portion of luminaire cost, has fallen to a level of the same order as the other luminaire components, such as the driver, housing, optics etc. With the current state of the technology, further luminaire performance improvement and cost reduction is realized most effectively by optimization of the whole system, rather than a single component. This project focuses on improving the integration between LEDs and drivers.

Lumileds has developed a light engine platform based on low-cost high-power LEDs and driver topologies optimized for integration with these LEDs on a single substrate. The integration of driver and LEDs enables an estimated luminaire cost reduction of about 25% for targeted applications, mostly due to significant reductions in driver and housing cost.

The high-power LEDs are based on Lumileds' patterned sapphire substrate flip-chip (PSS-FC) technology, affording reduced die fabrication and packaging cost compared to existing technology. Two general versions of PSS-FC die were developed in order to create the desired voltage and flux increments for driver integration: (i) small single-junction die (0.5 mm^2), optimal for distributed lighting applications, and (ii) larger multi-junction die (2 mm^2 and 4 mm^2) for high-power directional applications. Two driver topologies were developed: a tapped linear driver topology and a single-stage switch-mode topology, taking advantage of the flexible voltage configurations of the new PSS-FC die and the simplification opportunities enabled by integration of LEDs and driver on the same board. A prototype light engine was developed for an outdoor "core module" application based on the multi-junction PSS-FC die and the single-stage switch-mode driver. The light engine meets the project efficacy target of 128 lm/W at a luminous flux greater than 4100 lm, a correlated color temperature (CCT) of 4000K and a color rendering index (CRI) greater than 70.

2. Objective and accomplishments

2.1. Objective

The overall goal of this project was to reduce system cost and improve system efficacy of LED lamps and luminaires by developing an integrated high-voltage light engine, combining LEDs and driver on a single substrate connected directly to mains input. The high-level targets were defined as an efficacy of 128 lm/W at a CCT of 4000K and CRI>70, and a cost reduction of 25% at luminaire level for targeted applications, relative to an equivalent luminaire with standalone driver.

The following objectives were defined in support of this overall goal:

- Development of a multi-junction patterned sapphire substrate flip-chip (PSS-FC) LED package with an efficacy of 160 lm/W, CCT of 4000K and CRI>70, at a current density $J=35\ A/cm^2$ and junction temperature $T_j=85\ °C$;
- Development of linear and switch-mode driver topologies and application circuits for integration with the developed LED packages;
- Design and development of an integrated light engine for a key target application with initial reliability study completed.

2.2. Summary of accomplishments

Relative to the objectives above, the following key accomplishments were made.

- Multi-junction 2 mm^2 PSS-FC die were developed and prototyped with various die designs ranging from 4 to 16 junctions per die. Fully packaged versions of the die showed an efficacy of up to 158 lm/W at 4000K, CRI>70, J=35 A/cm^2 and T_j=85 °C; 1.3% short of the160 lm/W LED efficacy target.
- An improved tapped linear driver circuit was developed, showing a reduction in flicker index from 0.30 to 0.12 while meeting power factor (PF) and total harmonic distortion (THD) specifications. A compact switch-mode driver topology with universal input voltage capability (120-277V AC) was developed, showing driver efficiency up to 92% and flicker index in the range of 0.03-0.06.
- A prototype light engine was developed for an outdoor "core module" application based on the multi-junction PSS-FC die and the single-stage switch-mode driver. Initial reliability tests including 500h wet high-temperature operating life (WHTOL) were completed by the end of the project.

The developed light engine meets the project efficacy target of 128 lm/W at a luminous flux greater than 4100 lm, a correlated color temperature (CCT) of 4000K and a color rendering index (CRI) greater than 70.

2.3. Milestone summary

A summary of the milestones and completion status is given in Table 1. This summary includes two revisions of the original milestones from the Statement of Project Objectives, which were made in alignment with the DOE Project Manager:

1. A split of the original Milestone 2.2.1 (Demonstration of driver topology) into two milestones, 2.2.1a and 2.2.1b for demonstration of a linear and a switch-mode topology, respectively; and delay of Milestone 2.2.1b from Month 6 to Month 12.
2. Specification of the final efficacy milestones (1.3.2 and 3.2.2) at a CCT of 4000K and CRI greater than 70 instead of the original CCT of 3000K and CRI of 80, to be more representative of the targeted outdoor application. The LED efficacy target values were translated accordingly.

All milestones were completed on time and met or exceeded the target performance, with the exception of Milestone 1.3.2, where the measured efficacy was 158 lm/W vs. a target efficacy of 160 lm/W.

Table 1: Milestone summary table (continued on next page).

Task #	Task Title	MS #	Milestone Description	Milestone Verification Process	Milestone Date	Milestone Status
1.1	HV PSS-FC die development	1.1.1	Die prototype demonstration	Functional PSS-FC blue die with Vf>10V; NIST calibrated optical / electrical measurement	M9 May 2015	Completed May 2015
1.2	Small PSS-FC die development	1.2.1	Die prototype demonstration with WPE of 60%	Functional PSS-FC blue die with size <1mm^2; NIST calibrated WPE measurement at Tj=85°C, J=35A/cm^2	M3 Nov 2014	Completed Nov 2014

1.3	Package integration	1.3.1	Intermediate efficacy demonstration, 130 lm/W (3000K/80CRI)	NIST calibrated efficacy measurement at Tj=85°C, J=35A/cm^2	M9 May 2015	Completed May 2015
1.3	Package integration	1.3.2	Final efficacy demonstration, target 160 lm/W (4000K/70CRI)	NIST calibrated efficacy measurement at Tj=85°C, J=35A/cm^2	M18 Feb 2016	Completed Feb 2016 **Actual value: 158 lm/W**
2.2	Driver topology development	2.2.1 (a)	Demonstration of linear topology	Functional prototype of discrete (non-integrated) implementation	M6 Feb 2015	Completed Feb 2015
2.2	Driver topology development	2.2.1 (b)	Demonstration of switched-mode topology	Functional prototype of discrete (non-integrated) implementation	M12 Aug 2015	Completed Aug 2015
2.3	Application circuit development	2.3.1	Application circuit complete	Measurement of prototype with efficiency, PF and THD meeting application specification	M15 Nov 2015	Completed Nov 2015
3.1	System modeling	3.1.1	Target application selection	Demonstration of benefit of driver integration through system calculations	M6 Feb 2015	Completed Feb 2015
3.2	Light engine design and development	3.2.1	Functional prototype demonstration	Functional prototype of discrete implementation of light engine with basic electrical and optical characterization	M12 Aug 2015	Completed Aug 2015
3.2	Light engine design and development	3.2.2	Final prototype efficacy demonstration, target 128 lm/W (4000K/70CRI)	NIST calibrated efficacy measurement under steady-state operating condition; system electrical and optical performance meeting application specification	M18 Feb 2016	Completed Feb 2016
3.3	Light engine reliability study	3.3.1	Initial reliability study complete	Completion of 500 h HTOL test	M18 Feb 2016	Completed Feb 2016

3. Project activities

3.1. LED development

Two emitter types based on the PSS-FC architecture were developed to create high-voltage LEDs and LED arrays with addressable voltage increments for optimal integration with linear and switch-mode drivers: (i) a 0.5 mm^2 single-junction emitter for distributed applications such as troffers and ceiling lights, which typically require a large array of small lumen packages to achieve uniformity; (ii) 2 and 4 mm^2 multi-junction emitters for directional applications such as streetlighting, parking areas, high-bay lighting and indoor spots, which require fewer and larger lumen packages to achieve the desired directionality.

Single-junction LED development

Based on PSS-FC die prototypes available at the beginning of the project, a 0.5 mm^2 PSS-FC die was developed in Q4-2014, incorporating several design and process improvements to increase wall-plug efficiency (WPE). The via contact arrangements were improved, without penalizing the forward voltage, and the die singulation process was improved to remove contaminants. The dies were packaged in a LUXEON Q type package, comprising a ceramic submount with reflective silver coating and silicone dome encapsulant as shown in Figure 1. WPE measurements were performed in a NIST calibrated integrating sphere at a current density of 35 A/cm^2 and a junction temperature of 85 °C. A box plot of the results (Figure 2) shows that the WPE exceeds 60%, meeting the WPE requirement of Milestone 1.2.1 (Nov 2014).

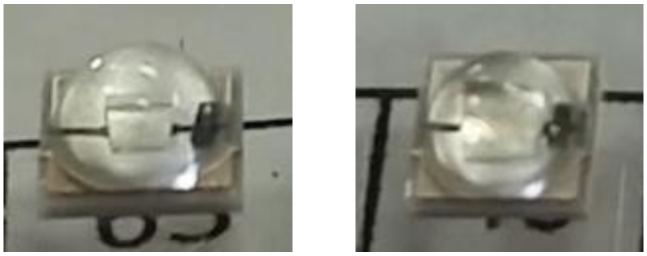

Figure 1: Packaged prototype PSS-FC devices with 0.5 mm^2 die area (left) and 1 mm^2 die area (right).

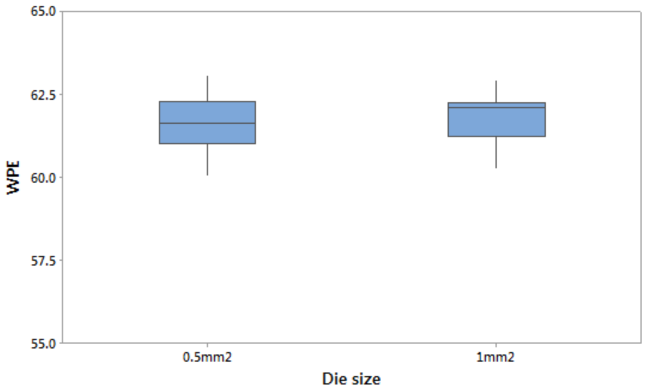

Figure 2: Boxplot of measured wall-plug efficiency of prototype PSS-FC devices. Results shown are for 97 devices with 0.5 mm^2 die area and 60 devices with 1 mm^2 die area.

Multi-junction LED development

The first round of high-voltage PSS-FC dies were fabricated in Q1-2015. The die design was based on a 2 mm^2 die and includes variations in die segmentation (4, 8, 12 and 16 junctions) and contact pad arrangement (2 pads and 4 pads). The dies were fabricated using a new process. An I-V curve for the 16-junction die is shown in Figure 3, demonstrating a functional die in fulfillment of Milestone 1.1.1 (May 2015).

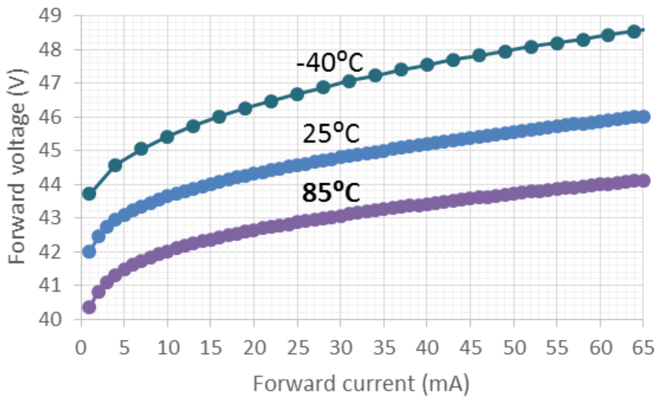

Figure 3: I-V measurements of 16-junction 2 mm^2 PSS-FC die prototype at a junction temperature of -40, 25 and 85 °C.

To evaluate the packaged LED efficacy of the new PSS-FC dies, 0.5 mm^2 single-junction die as well as 2 mm^2 4-junction die were packaged in a LUXEON Q type package with a phosphor coating targeted at a CCT of 3000K with CRI>80. Selected packages were characterized in a calibrated integrating sphere at a junction temperature of 85 °C and a current density (by die area) of 35 A/cm^2. Table 2 shows results for both die types. The package based on the 0.5 mm^2 die exceeds the mid-project target efficacy of 130 lm/W, satisfying the success criteria for Milestone 1.3.1 (May 2015).

Table 2: Packaged LED characterization results.

Die type	**0.5 mm^2**	**2 mm^2 4J**
T_j (°C)	85	85
I_f (mA)	175	175
V_f (V)	2.73	11.01
Flux (lm)	62.6	248.3
Efficacy (lm/W)	131.0	128.9
CCT (K)	3116	3160
CRI R_a	83.5	83.5
CRI R_9	8.0	8.1

A systematic photometric characterization study of the high-voltage PSS-FC dies was conducted. The study covered five die designs (4 multi-junction designs and 1 single-junction control) and two die configurations. More than 250 samples of each die type were packaged in a LUXEON Q package with phosphor targeted at a CCT of 4000K and a CRI greater than 70. Inline photometric measurement results of all parts were calibrated using measurements of selected parts in a NIST calibrated integrating sphere at a junction temperature of 85 °C and a test current defined as 700 mA divided by the number of junctions (corresponding to an effective current density of 35 A/cm^2 by die area).

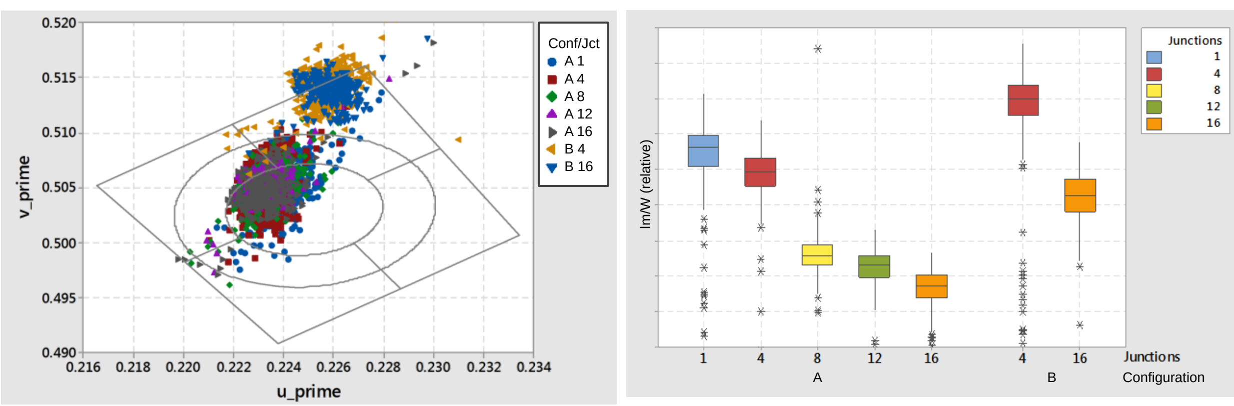

Figure 4: Chromaticity (left) and relative luminous efficacy (right) of LUXEON Q emitters with 2 mm^2 high-voltage PSS-FC die, measured at J = 35A/cm^2 and T_j = 85°C.

Figure 4 shows the relative efficacy of the samples as well as their chromaticity. The 4-junction die in configuration B exhibited the highest efficacy at 146 lm/W. The efficacy declines slightly with increasing number of junctions due to the smaller area available for electrical contacts (effectively leading to a higher local current density). The efficacy increases slightly going from configuration A to configuration B, likely due to improved package efficiency. Knowledge of these dependencies enables system-level optimizations that take into account the impact of high LED voltage on both LED and driver performance.

Subsequent die development activities in the project focused on further improving efficacy of the PSS-FC based LEDs with an improved die design. Extensive simulations were carried out on optical and electrical designs of the structure. Process development was carried out and prototype parts were made to check performance improvements towards the targets as well as reliability.

A second fabrication round of the 2 mm^2 multi-junction PSS-FC emitter was conducted in Q4-2015 and Q1-2016. The fabrication incorporated improvements in epitaxy, phosphor and package to increase the efficacy towards the final project target of 160 lm/W; the abovementioned die improvements were not ready at the time of the build and were not included. All of the eight die designs previously prototyped were again included in this build; these include variations in die segmentation (4, 8, 12 and 16 junctions, as well as a 1-junction control) and contact pad arrangement (2 pads and 4 pads). The die were packaged in a LUXEON Q package with an upgraded phosphor system with improved conversion efficacy (CE) and color-over-angle uniformity (CoA), targeted at a CCT of 4000K and a CRI greater than 70. In addition to the different die designs, the build matrix included two variations of epitaxy design and die configurations A and B.

Over 5000 white LUXEON Q parts were built in total. Inline photometric measurement results of all parts were calibrated using measurements of selected parts in a NIST calibrated integrating sphere. Compared to the previous build from May 2015, a median efficacy gain of 2.6% was measured for equivalent parts. Figure 5 shows the relative efficacy and forward voltage for the parts with configuration A. Similar to the previous build, the efficacy declines slightly with increasing number of junctions; furthermore, the results show a small efficacy gain of one of the epitaxy design variations, partly due to a lower forward voltage.

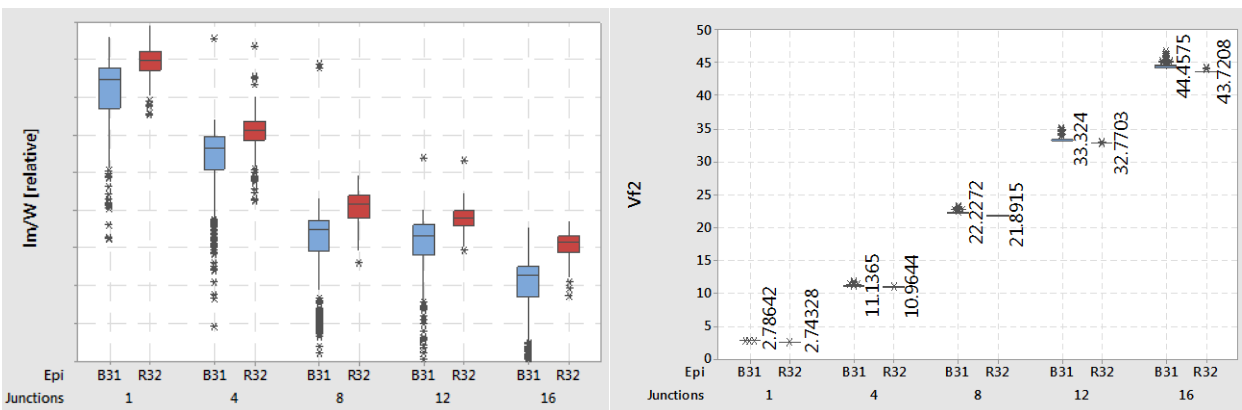

Figure 5: Measured efficacy (left) and forward voltage (right) of PSS-FC LEDs in LUXEON Q package as a function of number of junctions and epitaxy design; measured at a junction temperature of 85°C and drive current of 700 mA divided by the number of junctions.

Figure 6 shows the chromaticity and efficacy vs. forward current of one of the 4-junction LEDs (which have the highest efficacy of the multi-junction LEDs in this build) at a junction temperature of 85 °C, measured using a NIST calibrated integrating sphere in fulfilment of Milestone 1.3.2 (Feb 2016). At a current of 141 mA, which corresponds to a current density of 35A/cm^2 by active area (defined by the p-contact area), the measured efficacy is 158 lm/W, 1.3% below the target efficacy of 160 lm/W. The CCT is 3779 K (within the 4000K ANSI bin) and the CRI R_a is 71.7.

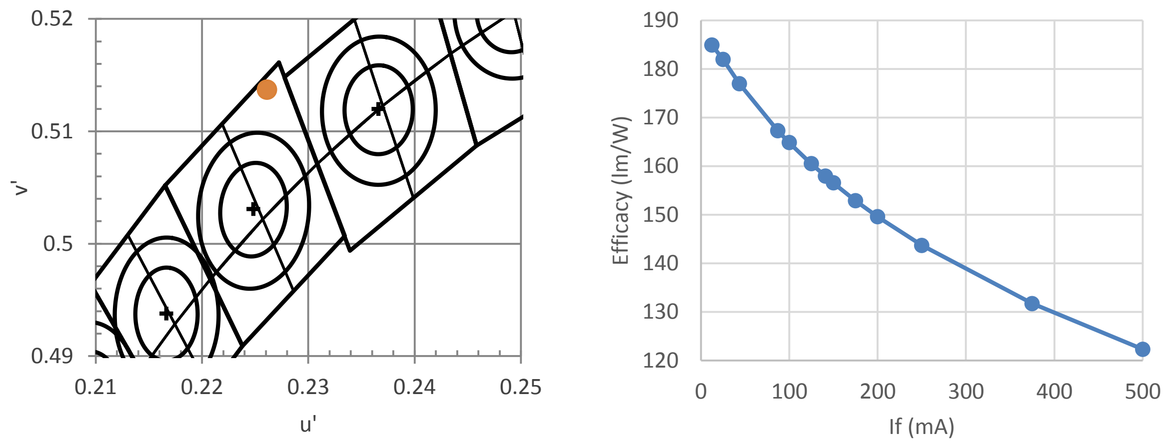

Figure 6: Chromaticity (left) and efficacy vs. drive current (right) of 4-junction PSS-FC LED for final LED efficacy demonstration milestone, measured at a junction temperature of 85 °C.

In addition to the 2 mm^2 multi-junction die, a 4 mm^2 multi-junction PSS-FC die based emitter was developed. The 4 mm^2 die based emitter leverages the existing 1 mm^2 PSS-FC die technology by establishing the electrical connection between the junctions in the submount to create a 4-junction emitter. This eliminates the need for rerouting in the die and provides a multi-junction PSS-FC LED for integration with the driver topologies developed in this project. The design of the emitter is based on a compact 4.0 mm x 4.0 mm package with full encapsulation. Nominal 3V and 12V versions are enabled by parallel and series routing in the submount, respectively.

3.2. Driver development

<u>Driver load voltage analysis</u>

In the first quarter of the project, linear and switch-mode driver topologies were analyzed to determine optimal values for the forward voltage of the high-voltage LEDs under various conditions, in order to guide the LED development described in the previous section. In a given application, the amount of LEDs and their (die) size are often dictated by the application flux and optical requirements. The approach was therefore to establish optimized LED voltages that can cover a wide range of applications with different amounts of LEDs.

For tapped linear drivers, the analysis was based on the premise that the total LED string voltage must be within a certain range (typically 80-95%) relative to the peak mains voltage in order to achieve good driver efficiency and LED utilization. Also, the parallel/serial arrangement of the LEDs must be such that all LEDs can be driven reasonably close to their normal operating current. Application of these boundary conditions allowed us to establish a set of die voltages that provide good coverage of relevant LED counts and mains voltages. For example, dominant mains voltages in North America are 120, 240 and 277 V. As shown in Table 1, these mains voltages can be mostly covered with two or three different die voltages.

Table 3: Example result of die voltage mapping for tapped linear drivers. Vf1, Vf2 and Vf3 represent three different die voltages. Green fields show the optimal die voltage for the given combination of LED count and mains voltage. Red fields indicate none of the three die voltages offers a solution.

# of LEDs	Mains voltage (V_{rms})		
	120	240	277
4	Vf2	-	-
6	Vf1	Vf3	-
8	Vf2	Vf2	Vf3
10	Vf2	-	Vf2
12	Vf1	Vf1	-
14	Vf1	Vf3	Vf1
16	Vf1	Vf2	Vf1
18	Vf1	Vf2	Vf3
20	Vf1	Vf2	Vf2
22	Vf1	Vf2	Vf2
24	Vf1	Vf1	Vf2

For switch-mode drivers, the requirements are generally less stringent in the case of dual-stage drivers as the second converter stage can be designed to deliver the appropriate output voltage for the LED string. Single-stage boost drivers require the LED string voltage to be higher than the peak mains voltage, while single-stage buck drivers require the string voltage to be lower.

The results from these analyses were used to define a preliminary set of die voltages to guide the first round of high-voltage PSS-FC die design in Task 1.

Tapped linear driver development

At the start of the project, a light engine with integrated tapped linear driver for an outdoor module application was designed and prototyped as a baseline for further driver development. The baseline light engine is shown in Figure 7. It contains 12 thin-film flip-chip (TFFC) LEDs with 4 junctions each in a LUXEON T package, and a tapped linear driver circuit based on a commercially available driver IC, all assembled on a single metal-core printed circuit board (MCPCB). The light engine operates at 120V AC input voltage, with a power factor of 0.994 and flicker index of 0.30.

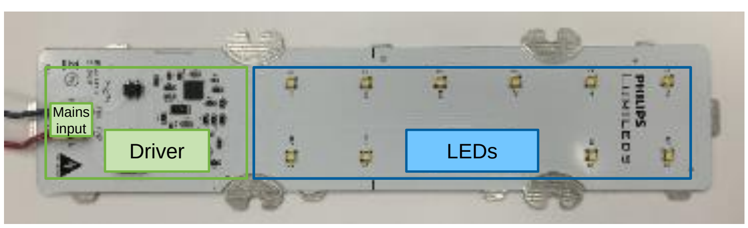

Figure 7: Baseline prototype LED light engine with integrated tapped linear driver.

An improved tapped linear driver (TLD) circuit was designed and implemented in fulfillment of Milestone 2.2.1a. The circuit achieves the following improvements over a baseline light engine:

- Reduced flicker while keeping power factor (PF) greater than 0.9 and total harmonic distortion (THD) less than 20%. This improvement is realized by adding a capacitor parallel to each LED substring.
- Analog step dimming capability to ~50% of maximum output power. This improvement

was realized by switching the current sense resistance in the reference TLD topology using an optocoupler with 5 V DC control input.

The design was implemented in a prototype based on a single-layer MCPCB with the same form factor as the baseline light engine. The prototype is shown in Figure 8. Table 4 shows key performance characteristics of the prototype compared to the baseline engine, demonstrating the improved flicker performance, both in dimmed and full-power condition.

Figure 8: Prototype light engine implementing improved TLD circuit.

Table 4: Measured performance of prototype compared to baseline light engine.

	Baseline	**Prototype**
Input Power (W)	33.0	31.4 (full power)
Power Factor	0.994	0.994
THD	10%	11%
Flicker Index	0.287	0.120 (full power) / 0.075 (dimmed)

<u>Switch-mode driver development</u>

For the switch-mode driver (SMD) circuit, a decision matrix was made to compare qualitatively the expected performance of various switch-mode topologies on key application specifications. The topologies included several single- and dual-stage converter variations. A topology was selected to take advantage of the high-voltage PSS-FC LEDs developed in Task 1 combined with excellent input performance, high efficiency and robustness for transient surges.

Switch-mode drivers have several known advantages compared to TLD, including higher efficiency, LED utilization and capability of a universal input voltage range. Potential disadvantages include higher component count (and hence cost) and larger form factor. To enable a close comparison with the improved TLD design, most specifications such as light output, dimmability, thermal constraints and surge protection were chosen similar to the TLD prototype.

A 16-junction PSS-FC die was selected for the first SMD design. Output capacitors were used to suppress flicker caused by current ripple at double the mains frequency. The high differential resistance R_d of the multi-junction LEDs substantially reduced the requirement for the output capacitance. The measured R_d of the 16-junction die was 34Ω at maximum current. LTSpice simulations (Figure 9) showed that with this R_d value, a capacitance of only 22 µF was needed to reduce current ripple to below the target maximum value of 20%.

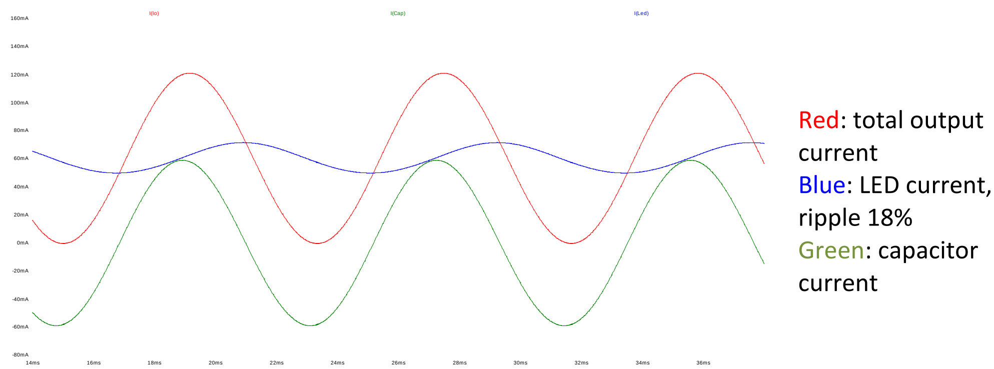

Figure 9: LTSpice simulation result of LED current ripple with 22uF capacitor.

In the first SMD design, the driver board and an LED board were designed separately to have flexibility in testing and debugging. Both designs were made on a single-layer metal-core printed circuit board with 100% surface mount technology (SMT) components. The LED board was populated with 16-junction PSS-FC LEDs in LUXEON Q package targeted at a CCT of 4000K and CRI greater than 70. The driver was designed to deliver an output power of approximately 28W and includes a simplified 0-10V dimming interface.

Basic operation of the driver was tested for 120V and 277V input voltage and different dimming levels, meeting the requirements of Milestone 2.2.1b. Figure 10a shows the input voltage and input current at 120V input voltage and full power, illustrating the high power quality under these conditions. The output current ripple was measured to be 27.5% peak to peak. Under operating conditions where the conduction time of the switching MOSFET is reduced, including dimmed operation at 120V and full output power at 277V, instable operation occurred. This was found to be mainly due to an electrical disturbance which was fixed in the prototype and permanently addressed in the design of the next iteration. Removal of the disturbance enabled stable operation at 120V for 10-100% output and at 277V for 100% output power (Figure 10b). Dimmed operation (10%) at 277V was not stable, in part due to the LED string voltage becoming critically low. This problem was resolved in the next design iteration by transitioning to a design with fourteen 12-junction LEDs, slightly increasing the load voltage.

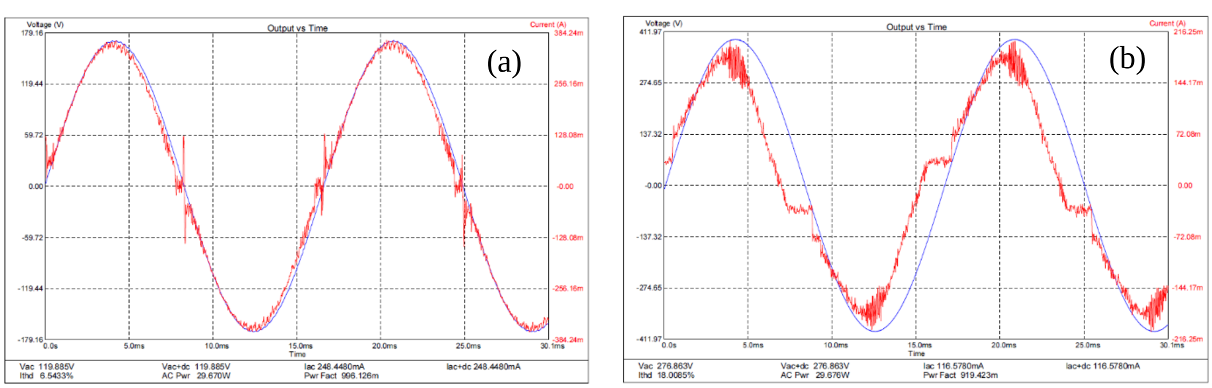

Figure 10: Input voltage (blue) and input current (red) at (a) 120V/60Hz input and (b) 277V/60Hz input.

The electrical performance of the first prototype driver is summarized in Table 5. This illustrates the capability of the switch-mode driver to achieve >90% driver efficiency, low current ripple (and hence low flicker) and universal input voltage, which are key discriminating benefits versus the tapped linear driver technology.

Table 5: Electrical characterization summary.

$V_{in, AC}$ (V)	P_{in} (W)	PF	THD (%)	I_{LED} (mA)	I_{LED} ripple (% pk-pk)	V_{LED} (V)	P_{out} (W)	Efficiency (%)
120	29.67	0.99	6.5	60	27.5	453	27.2	91.6
277	29.67	0.92	18	60	27.5	453	27.2	91.6

In the second design iteration, the driver circuit and PSS-FC LEDs were integrated onto a single MCPCB. An LED array of fourteen 12-junction PSS-FC LEDs in series was used. The LEDs were packaged in a LUXEON Q package with a CCT of 4000K and CRI greater than 70. Compared to the initial demonstration, the output capacitors were changed to have higher voltage rating (allowing for a wider operating range) and lower capacitance (to keep similar footprint). Design improvements were implemented to mitigate the disturbance found in the first prototype.

Electrical characterization results of the light engine are summarized in Table 6. The driver meets power quality requirements and shows high efficiency of more than 90% throughout the input voltage range of 120-277V, meeting the criteria for Milestone 2.3.1.

Table 6: Electrical characterization results of the light engine shown in **Error! Reference source not found.**.

V_{in} (VAC)	P_{in} (W)	PF	THD (%)	I_{LED} (mA)	I_{LED} ripple (% pk-pk)	V_{LED} (V)	P_{out} (W)	Efficiency (%)
120	32.43	0.99	5.6	63	38.2	472	29.7	91.6
230	32.13	0.97	14.9	62	43.4	472	29.3	91.3
277	32.47	0.94	18.6	62	45.3	471	29.3	90.2

3.3. Integration and product development

Target application selection

An outdoor "core module" was selected as target application for the light engine to be developed. The core module is a high-power LED light engine delivering about 4000 lumens for street and roadway lighting applications. The outdoor applications that this product is used in may have a mains voltage of 120V, 240V or 277V; all of which are present in significant numbers in the current installed base. Therefore, compatibility with all these voltages is typically required. This makes the product a good use case for the development of integrated switch-mode drivers, in which universal mains voltage is a key advantage over tapped linear drivers. Furthermore, the outdoor applications relevant to this product typically require high-power LEDs because of their high brightness, good color-over-angle uniformity and reliability. Driver-on-board integration with high-power LEDs had been underdeveloped compared to mid-power LEDs (due to the more challenging power requirements and incompatibility of voltage/flux increments in existing high-power LEDs). The PSS-FC based LEDs to be developed in Task 1 of this project are designed to facilitate driver integration and open up these additional application segments. These attributes make the outdoor core module an ideal target application for the light engine.

A system cost analysis was completed for the outdoor core module, considering the luminaire-level effects of moving to the proposed light engine architecture comprising low-cost PSS based LEDs and an integrated driver, under the assumptions of constant luminaire light output and efficacy. The luminaire was a streetlight with a light output of 5000 lm at a CCT of 4000K and a CRI greater than 70. The integrated driver was assumed to be a generic TLD topology. The results of the cost analysis are shown in Figure 11.

Moving from an external driver to an integrated TLD without changing the LED type can be seen to affect the system cost in three major ways:

- More LEDs are needed to maintain light output and efficacy due to the lower utilization of LEDs in a TLD, which drives the LEDs at zero or low current during part of the mains cycle. This leads to an increase in the LED cost.
- The driver bill-of-materials (BOM) cost is significantly lower due to the simple design and low component count of the TLD.
- The housing cost is reduced because there is no need for a separate space or compartment to accommodate the driver. This allows the housing to be substantially smaller and enables the use of lower-cost materials and processes.

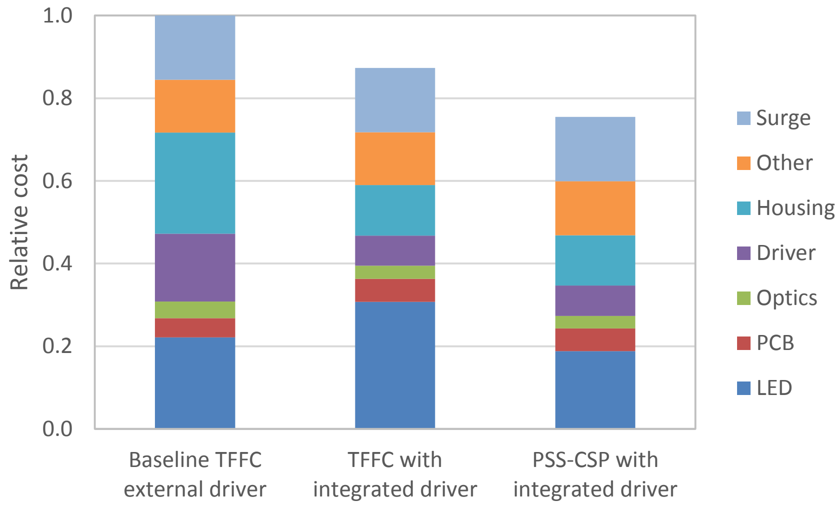

Figure 11: System cost breakdown of streetlight with outdoor core module based on proposed PSS-CSP with integrated driver compared to baseline TFFC with external driver.

Overall, the driver and housing BOM reduction more than offsets the increase in LED cost and the luminaire cost is about 13% lower than baseline. Additional cost reduction can be achieved by low-cost PSS-based LEDs. The overall system cost is then reduced to approximately 75% of the baseline. The system cost analysis confirms the ability of the outdoor core module to achieve the project system cost objective (Milestone 3.1.1).

Light engine integration

Several SMD-based light engine prototypes were made throughout the project. The first discrete light engine demonstration was based on the initial driver prototype combined with a board of 16-junction PSS-FC LEDs in LUXEON Q package targeted at a CCT of 4000K and CRI greater than 70. The complete light engine assembly, meeting Milestone 3.2.1, was characterized in a 1-meter integrating sphere on a temperature-controlled stage with 120V/60Hz input at full output power and three different stage temperatures, as shown in Table 7. At a heat sink temperature of 60 °C, the light engine efficacy was measured to be 107 lm/W.

Table 7: Results of photometric characterization with 120V/60Hz input at full output power.

T_{stage} (°C)	P_{in} (W)	Flux (lm)	Efficacy (lm/W)	Flicker index	CCT (K)	CRI Ra
25	31.11	3380	108.6	0.033	3896	75.1
60	30.69	3286	107.0	0.033	3961	76.0
85	30.26	3147	104.0	0.035	4017	76.7

The final light engine demonstration (Milestone 3.2.2) is a fully integrated light engine prototype incorporating the improved LEDs described in Section 3.1 as well as the driver design changes described in Section 3.2. The light engine, shown in Figure 12, uses an array of fourteen 12-junction PSS-FC LEDs in LUXEON Q package targeted at a CCT of 4000K and CRI greater than 70. Light engine efficacy improvements relative to the first demonstrator are enabled by the LED performance upgrades and reduced drive current.

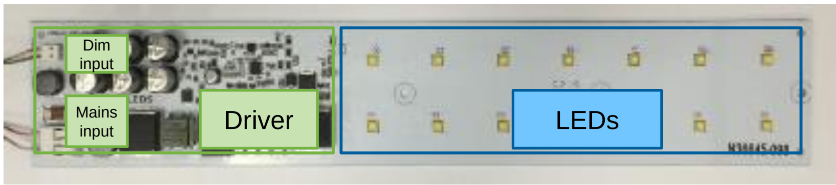

Figure 12: Final integrated light engine prototype.

Photometric characterization of the light engine was performed in a 1-meter integrating sphere. Figure 13 shows the chromaticity at full output power and the flux and efficacy as a function of dimming input, at a mains input voltage of 120V AC. At full output power, a flux of >4100 lm and efficacy of 128 lm/W were measured, meeting the target light engine efficacy of Milestone 3.2.2. The light engine also meets power factor (PF), total harmonic distortion (THD) and flicker requirements, and shows consistent performance across the input voltage range as shown in Table 8.

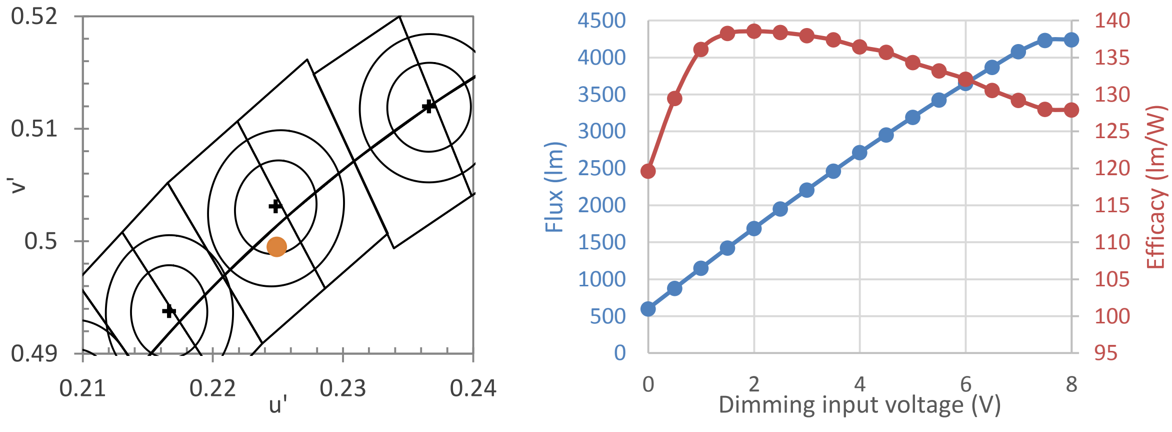

Figure 13: Chromaticity (left) and flux and efficacy vs. control input voltage (right) for the light engine shown in Figure 12, measured at a mains input voltage of 120V AC.

Table 8: Performance characteristics of the light engine shown in Figure 12 for three key input voltages within the universal input voltage range.

Voltage (V)	Current (A)	Power (W)	Frequency (Hz)	Flux (lm)	u'	v'	CCT (K)	CRI R_a	PF	THD (%)	Flicker Index
120	0.28	33.1	60	4181	0.2249	0.4997	4048	70.9	1.00	5.3	0.057
230	0.15	32.3	50	4118	0.2249	0.4997	4050	71.0	0.96	16.0	0.076
277	0.13	32.8	60	4131	0.2250	0.4996	4049	71.0	0.93	19.9	0.066

Reliability tests

Reliability tests were conducted on samples from the integrated light engine prototype build from Q4-2015. A test matrix was designed to test the driver and driver integration part of the light engine. The wet high-temperature operating life (WHTOL) test completed 800 hours as of the end of the project, meeting the 500-hour requirement of Milestone 3.3.1. The test was not passed because of a failure of the film capacitor after the mains bridge rectifier, which was observed in several of the samples. Alternative components have been identified to prevent this failure mode.

Technology development and release

In order to enable the design of custom "built-to-spec" light engine products, an internal technology development process was conducted concurrently with the development of the two driver topologies in this project. This is a phase-gate process ensuring that project quality criteria are met and risks are identified and mitigated as appropriate for the phase of the project. The TLD-based light engine technology was internally released in Q3-2015; the SMD-based light engine technology for the developed topology is scheduled to be internally released in Q2-2016.

4. Products

4.1. LED products

The technology developed to improve performance of 0.5 mm^2 single-junction PSS-FC dies has been incorporated in the LUXEON FlipChip White 05 product, which was released to the market in September 2015 (http://www.lumileds.com/products/high-power-leds/luxeon-flipchip-white).

4.2. Publications and presentations

Poster Presentation: "High-Voltage LED Light Engine with Integrated Driver", DOE SSL R&D Workshop, San Francisco, CA, January 27-29, 2015

Poster Presentation: "High-Voltage LED Light Engine with Integrated Driver", DOE SSL R&D Workshop, Raleigh, NC, February 2-4, 2016

4.3. Inventions and Patent Applications

Invention: Fred Song, Wouter Soer, Ron Bonné, Yifeng Qiu, "Dimmable AC Input LED Driver"

Invention: Fred Song, Wouter Soer, Ron Bonné, Yifeng Qiu, "Printed Circuit Board for Integrated LED Driver"