High-Luminance LED Platform for Improved Efficacy in Directional Applications

Final Technical Report

Federal Agency	U.S. Department of Energy
Sponsoring Program Office	EERE – Building Technologies Office
Award Number	DE-EE0008715
Award Type	Cooperative Agreement
Project Title	High-Luminance LED Platform for Improved Efficacy in Directional Applications
Report	Final Technical Report
Report Number	DOE-LL-0008715-1
Report Period Covered	April 1, 2019 – June 30, 2021
Recipient	Lumileds LLC 370 West Trimble Road San Jose, CA 95131
Principal Investigator	Dr. Wouter Soer wouter.soer@lumileds.com

This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Building Technologies Office, Solid State Lighting Program Award Number DE-EE0008715.

1. Executive summary

In this project, Lumileds developed a platform of high-luminance LEDs and LED light engines to increase efficacy and reduce energy consumption of directional lighting applications. The platform was developed through innovations in three key areas: (1) epi and device architectures optimized for high drive current density, breaking through the tradeoff in efficacy (lm/W) vs. emittance (lm/mm^2) exhibited by state-of-the-art products; (2) a compact chip-scale package allowing high packing density and thus high overall luminance in multi-emitter arrays; and (3) phosphor technology to enable correlated color temperature (CCT) tuning in multi-emitter arrays with optimized LED utilization, efficacy, color uniformity and color quality.

Directional indoor and outdoor lighting applications make up a major portion of the total lighting energy consumption in the U.S, accounting for >40% of the energy savings potential of solid-state lighting. Success of this project helps accelerate the realization of these energy savings both through higher system efficacy and adoption due to new functionality, and thus contributes significantly to realizing the DOE Lighting program goals.

2. Objectives and accomplishments

2.1. Objective

The goal of this project was to develop a high-luminance LED platform for directional lighting applications. The LED platform is based on a surface-emitting chip-scale package incorporating a 1 mm^2 die with minimal package size to facilitate packing in dense arrays. The LED is implemented in a range of white colors for fixed CCT applications and a set of phosphor-converted red, green and blue colors for CCT tunable applications. Efficacy improvements were targeted at the LED level and module level. At the LED level, the efficacy target was 120 lm/W at a luminous emittance of 150 lm/mm^2 and junction temperature of 85 °C, for a CCT of 4000K and CRI>80. At the module level, the efficacy targets were 128 lm/W for a fixed CCT module having CCT of 4000K and CRI>80, and 105 lm/W for a CCT tunable module having CRI>90 over a CCT range from 2700K to 6500K, both evaluated at a module emittance of 80 lm/mm^2 and junction temperature of 85 °C.

2.2. Summary of accomplishments

The final efficacy results at LED and module level are summarized below. All performance targets were met.

- LED efficacy: demonstrated **123 lm/W** vs. target of 120 lm/W
  (CCT ~ 4000K, CRI Ra>80, T_j = 85 °C, M_v = 150 lm/mm^2)
- Fixed CCT module efficacy: demonstrated **135 lm/W** vs. target of 128 lm/W
  (CCT ~ 4000K, CRI Ra>80, T_j = 85 °C, M_v = 80 lm/mm^2)
- Tunable CCT module efficacy: demonstrated **105 lm/W** vs. target of 105 lm/W
  (CCT ~ 4000K, CRI Ra>90, T_j = 85 °C, M_v = 80 lm/mm^2)

3. Project activities

3.1. HL LED efficacy improvement

The LED-level efficacy improvement effort concentrated on epi and die designs optimized for the specific attributes of the targeted high-luminance LED. The LED is an InGaN die with a patterned-sapphire substrate flip-chip (PSS-FC) device architecture.

Epitaxial design must consider the current density of the device in operation, since the various loss mechanisms have different dependencies on current density. For this project, the epi design goal was to yield maximum external quantum efficiency (EQE) at a target operating current density of approximately 50 A/cm^2. Experimental PSS patterns were also fabricated with the goal of improving light extraction while maintaining epi material quality.

The die development focused on improving the reflectivity of the die, which is particularly important in high-luminance LEDs since the package must be kept small to maintain high luminance, resulting in a higher number of photon bounces inside the die compared to package architectures that utilize a dome encapsulant or reflective cup for light extraction. Experiments were performed to improve the reflectivity of the composite reflector stack that comprises the p-contact as well as to optimize the die layout to reduce absorptions in and around contact vias.

Two controlled LED builds were conducted to measure the progress in the concurrent epi and die development during the course of the project. In both cases, experimental die and control die were built into white LEDs with representative phosphor and package to verify that the improvements did not have an adverse impact on conversion efficiency or package efficiency. The first build, performed in month 6, showed a 2.0% gain (milestone target 1.5%), while the second build, performed in month 21, showed a 3.4% gain (milestone target 3.0%) as demonstrated in Figure 1. Additional experimental design variations were included in the final performance demonstration, with results suggesting further gains, however these gains were not quantified as control devices were not included in this final demonstration.

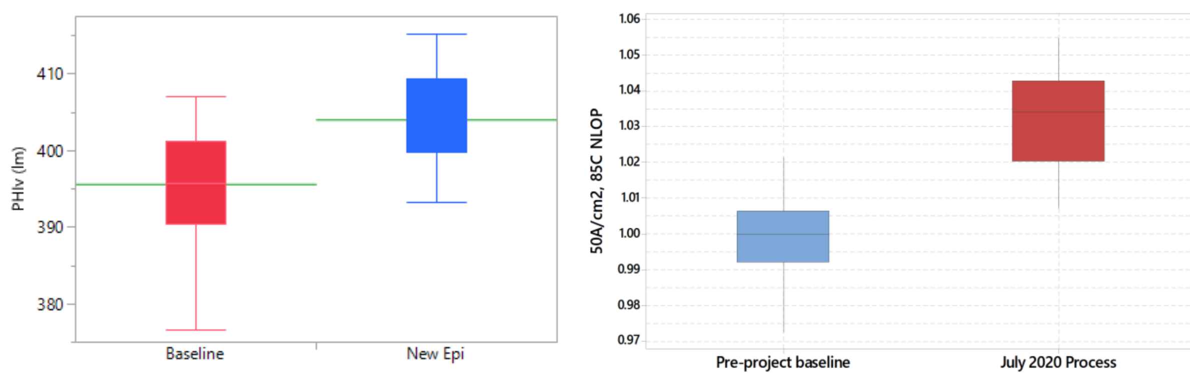

Figure 1: Luminous flux relative to pre-project baseline of white LED packages at a current density of 50 A/cm^2 and junction temperature of 85 °C. Left: month 6 build showing 2.0% gain; right: month 21 build showing 3.4% gain.

3.2. HL LED device architecture development

As the baseline for the device architecture development in this project, we used a state-of-the-art high-luminance LED, which was released to the market around the start of the project as LUXEON CSP HL1. This LED has a 1414 (1.4 mm x 1.4 mm) footprint and uses a 1 mm^2 PSS-FC die. Figure

2 shows an on-axis luminance image of the baseline LED, from which the source size at 50% luminance threshold was determined to be 1.23 mm^2.

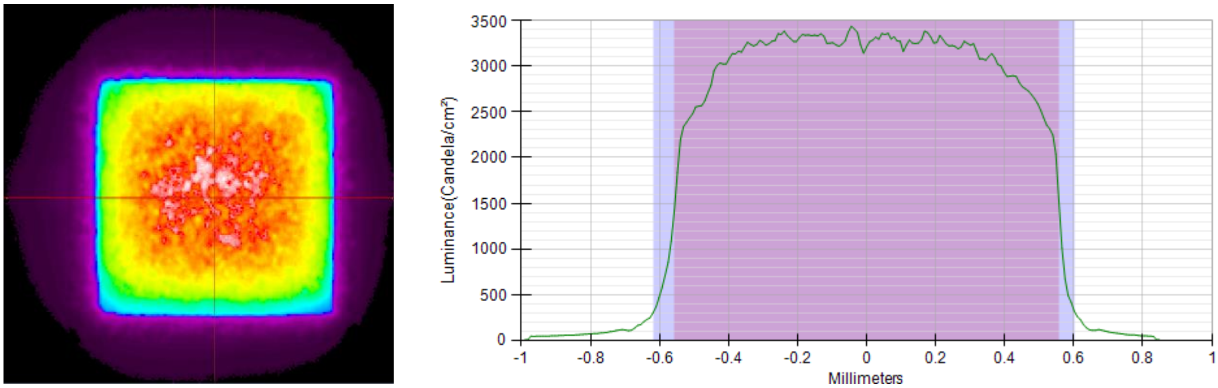

Figure 2: On-axis luminance image (left) and luminance cross-section profile (right) of baseline LED package showing a source size of 1.23 mm^2 based on a 50% luminance threshold.

The epi and die improvements of Year 1 were implemented in this 1414 HL1 LED in an experimental sample build. Photometric measurements of luminous flux and efficacy were performed for ten samples with nominal CCT of 4000K and CRI Ra>80 at a junction temperature of 85 °C and multiple currents up to 1500 mA. Figure 3 shows the resulting luminous efficacy vs. luminous emittance as calculated with the abovementioned source size for the experimental samples (improved) as well as production samples (baseline). At an emittance of 150 lm/mm^2, the experimental samples show luminous efficacy of 110 lm/W, meeting the Year 1 performance target.

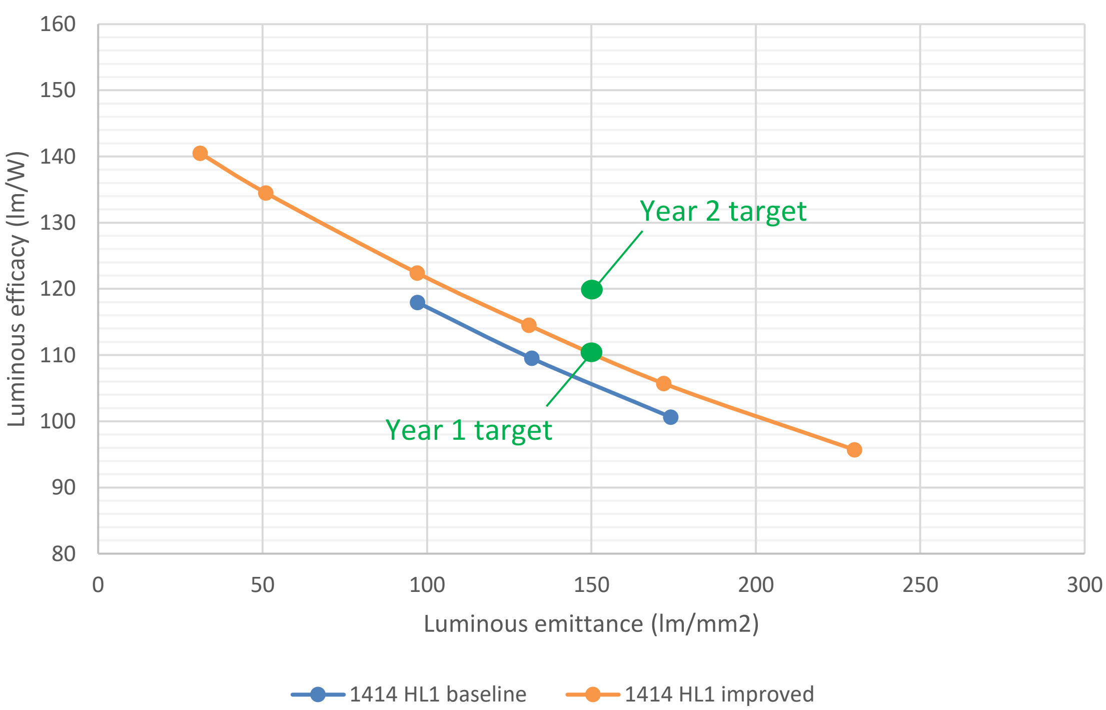

Figure 3: LED-level luminous efficacy vs. emittance of devices with baseline package architecture: production samples (1414 HL1 baseline) and samples with Year 1 epi and die improvements included (1414 HL1 improved). All data measured at T_j = 85 °C.

While the baseline LED architecture could support this LED-level performance target, it was anticipated in the project plan that it would not support the final module-level performance targets of the project. This is because the package includes a thick reflective coating around the perimeter of the die which adds significant dark area in densely packed arrays. An evaluation matrix of different device architecture types that could meet the project objectives was defined. The purpose of this matrix was to benchmark the proposed approach of a thin-film side coating (TFSC) against alternative options in order to identify the best solution and mitigate technical risk by having fallback options available. The matrix included variations in the type of side coating (thin film reflector resulting in a 1111 footprint package, and thick reflector preserving the 1414 footprint baseline but with enhancements for improved light extraction) and variations in the extent of emission confinement to the top surface (coatings covering the entire side of the package, and coatings covering only the die and leaving the phosphor exposed on the side).

Simulations were carried out in LightTools using models of the high-luminance devices with a phosphor system targeted at 4000K. LEDs were modeled on a white PCB, and periodic boundary conditions were defined to simulate nearest-neighbor interactions in an infinite array. The modeling results indicate that with a side coating that leaves the phosphor exposed on the side of the device, some cross-talk occurs in densely packed arrays in the form of color shift. However, the color shift is limited to about 1-2 points in CIE1976 color space, which is considered acceptable in practical applications. Subsequent development therefore focused on package variations with exposed phosphor because of the simpler processing and higher flux.

A 1111 footprint HL LED prototype (Figure 4) was developed through several iterations of design and process development. This package uses a thin film reflector on the sidewalls of the PSS-FC die to confine light emission to the top surface of the die. The phosphor element does not have a side coating.

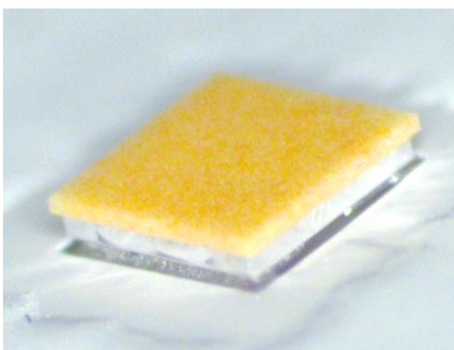

Figure 4: Prototype HL LED with 1111 footprint (nominal size 1.06 mm x 1.06 mm) using thin film reflector on the sides of the die.

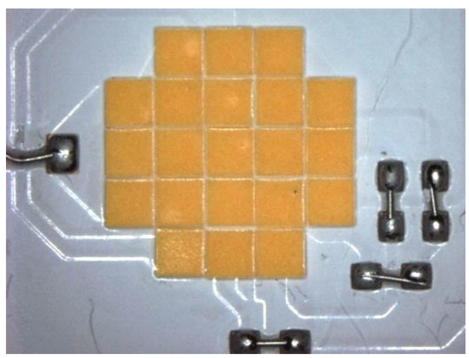

Figure 5: Module with the HL LEDs of Figure 4 densely packed in a 21-up array.

To assess the module-level performance of these prototype HL LEDs, printed circuit boards (PCBs) were designed to fit 21 LEDs at the closest possible pitch of 1.1 mm (leaving a gap of approximately 40 µm between the nominally 1.06 mm size LEDs). The PCBs were fabricated and two modules were assembled with LEDs having a nominal CCT of 4000K and CRI Ra>80 (Figure 5). Photometric characterization was performed of both the individual LEDs and the assembled modules. The results showed a color shift of ~ 5 points from the individual LEDs to the assembled modules, which is higher than the model prediction, possibly due to the slightly different geometry. No loss in radiant flux was observed between the individual LEDs and assembled modules.

The module-level efficacy vs. emittance was evaluated using a source size of 25.4 mm^2 as shown in Figure 6. Benchmark modules assembled using the baseline 1414 footprint LED with Year 1 epi and die improvements (at 1.5 mm pitch) are included for reference. As seen in this figure, the dense packing of the 1111 prototype LEDs enables the benchmark emittance of 80 lm/mm^2 to be achieved at significantly lower current density, resulting in higher efficacy and realizing significant progress towards the final project target of 128 lm/W. However, disadvantages of this approach are a relatively complex LED fabrication process and the higher LED count (and hence cost) to realize a target flux level with the reduced current density. To mitigate these disadvantages we also investigated alternative approaches in the design matrix.

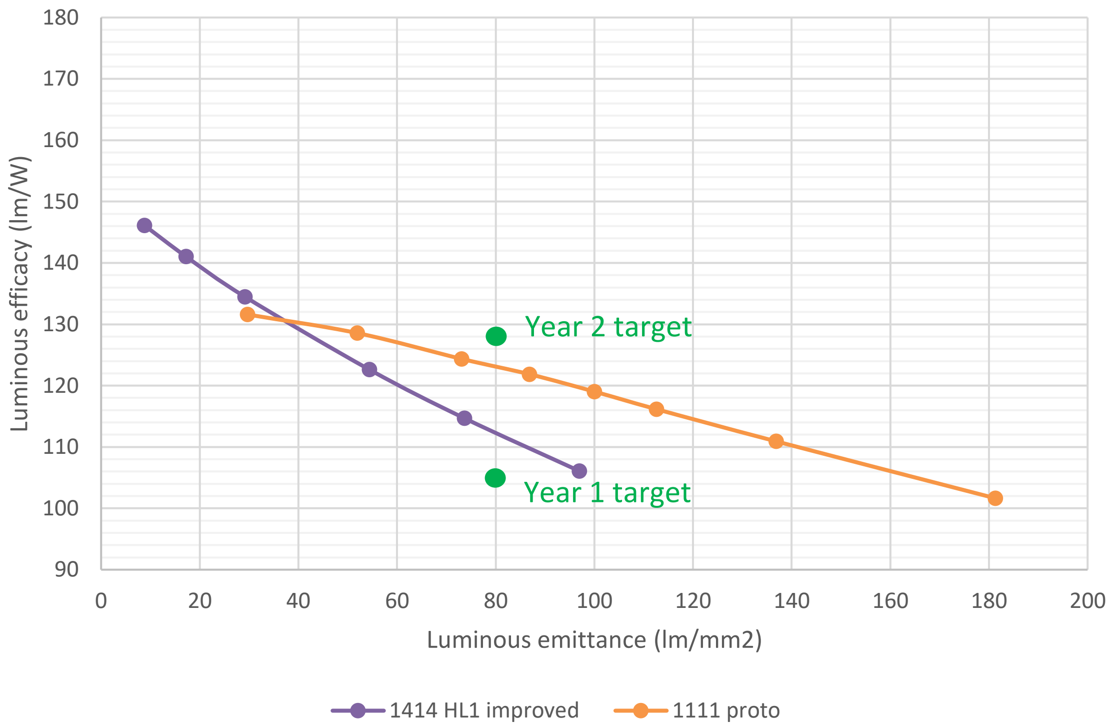

Figure 6: Module-level luminous efficacy vs. emittance of densely packed HL LED arrays: baseline LED architecture with Year 1 epi improvements (1414 HL1 improved) and 1111 prototype samples with comparable epi and die technology (1111 proto). All data measured at T_j = 85 °C.

Prototypes of a 1414 footprint HL LED with exposed phosphor sides were designed and fabricated to compare their performance against the 1111 prototype LEDs. Figure 7 shows an image of this prototype LED; an array is shown Figure 8. From luminance image measurements shown in Figure 9, the source size at 50% luminance threshold was determined to be 1.45 mm^2 (vs. 1.23 mm^2 for the baseline 1414 HL1, and 1.12 mm^2 for the 1111 proto). Moreover, only ~82% of flux is emitted from within this source area as the emission extends significantly further; in the 1414 HL1 and the 1111 proto LEDs, this percentage is close to 100%. As a result, normalized emittance for the 1414 prototype LED is relatively low; however, efficacy is substantially improved by the package design and the exposed phosphor element.

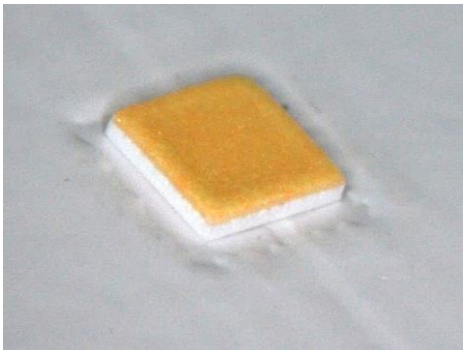

Figure 7: Prototype HL LED with 1414 footprint. The die is enclosed in reflective material while the phosphor is exposed on the sides.

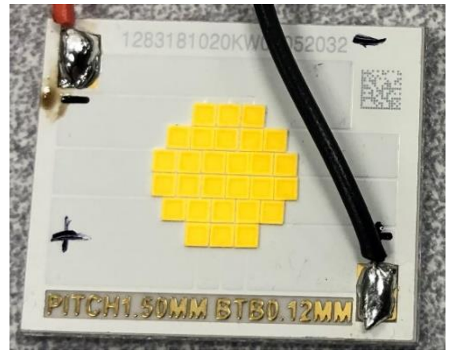

Figure 8: Module with the HL LEDs of Figure 7 densely packed in a 28-up array.

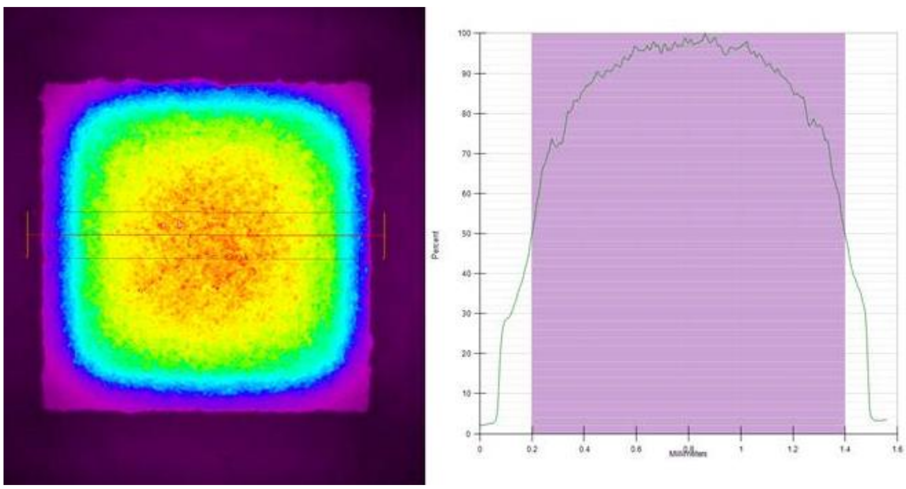

Figure 9: On-axis luminance image (left) and luminance cross-section profile (right) of prototype HL LED package showing a source size of 1.45 mm^2 based on a 50% luminance threshold.

The assembled module shown in Figure 8 accommodates the LEDs at a pitch of 1.5 mm, leaving a 0.1 mm gap between the nominally 1.4 mm sized packages. Photometric characterization of this module (with the LEDs including the Year 1 epi and die improvements) was conducted to compare its performance with the previously made prototypes. As shown in Figure 10, at the benchmark emittance of 80 lm/mm^2, the module with the 1414 prototype LED outperforms the module with the 1111 prototype LED and already meets the final module-level efficacy target, even though the final epi and die improvements are not yet included (intermediate performance demonstration). Only at significantly higher emittance does the 1111 prototype-based module gain an advantage; however, such high emittance levels are however not commonly used or required in illumination applications. Based on this comparison, the 1414 prototype device was selected for final performance demonstration.

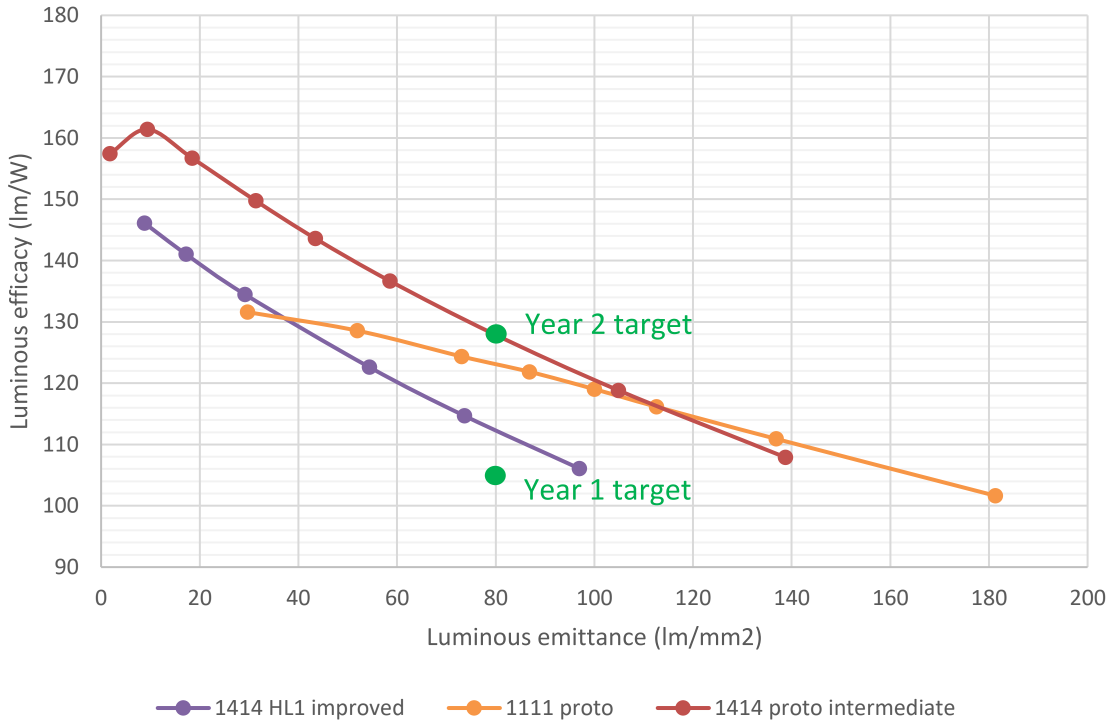

Figure 10: Module-level luminous efficacy vs. emittance of densely packed HL LED arrays: baseline LED architecture (1414 HL1 improved), 1111 prototype, and 1414 prototype (1414 proto intermediate), all with comparable epi and die technology. All data measured at T_j = 85 °C.

3.3. Platform for CCT tuning

A set of three phosphor-converted primary LED spectra was designed to be implemented in the HL LED package to enable CCT tuning in high-luminance modules. An advantage of using three dedicated primary spectra rather than linear CCT tuning between two white LEDs is that the average utilization of the LEDs and hence module-level emittance is substantially higher. Moreover, the use of three primaries allows precise tracking of the blackbody locus and color points off the blackbody locus.

Modeling of primary spectra and color points was carried out for the LUXEON CSP HL1 baseline device architecture. The modeling target was to maximize the minimum flux out of an RGB triplet between 2700K and 6500K, with boundary conditions of CRI Ra>90 and R9>50.

Engineering samples of the LUXEON CSP HL1 device with the targeted spectra of the three primaries were built and assembled into modules. Figure 11 shows a module with 21 LEDs (7 for each primary) arranged within a light emitting source area of about 9 mm in diameter. The modules were characterized in an integrating sphere with individual strings lit up separately at a drive current of 350 mA and junction temperature of 85 °C. The performance at different CCTs was calculated by mixing the individual string data at this nominal test condition (which would be representative of PWM drive mode). The flux as a function of CCT is shown in Figure 12. The minimum flux maintained over the CCT range 2700-6500K with a CRI Ra>90 and R9>50 is 1155 lm.

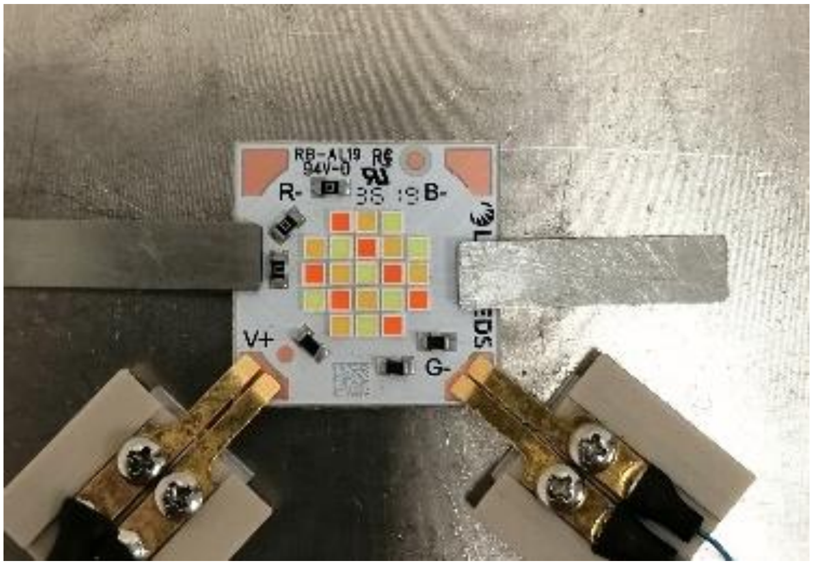

Figure 11: Prototype module with LUXEON CSP HL1 samples of desaturated RGB primaries.

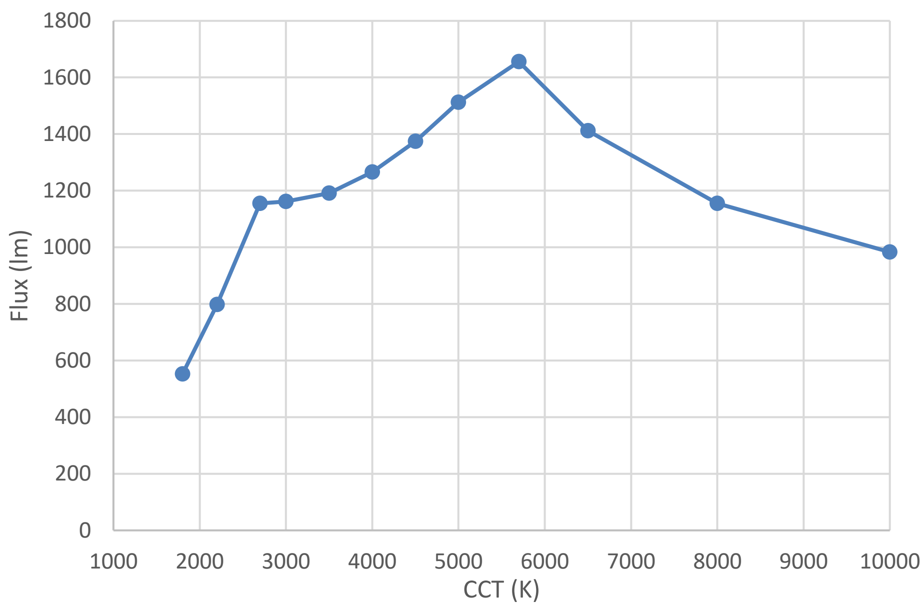

Figure 12: Luminous flux of module in Figure 10 as a function of CCT at a drive current of 350 mA and junction temperature of 85 °C.

3.4. Final performance demonstration

The epi and die technology improvements made over the course of the project (shown in Figure 1) were incorporated in a wafer fabrication lot together with further experimental variations in epi design. The resulting die were packaged into 1414 prototype devices with four different color targets: a white color point having a nominal CCT of 4000K and CRI Ra>80, and the three primary red, green and blue color points for CCT tuning with CRI Ra>90 and R9>50.

Figure 13 shows efficacy vs. emittance of the final white demonstration devices compared to other intermediate performance demonstrations reported earlier. At a luminous emittance of 150 lm/mm^2, the luminous efficacy is 123 lm/W, showing significant improvement over the intermediate demonstration with this same device architecture (owing to the epi and die improvement included in this final demonstration), and exceeding the 120 lm/W project target. At this emittance, the average CRI Ra was measured to be 80.2 with a CCT of 4008 K and Duv = +0.004.

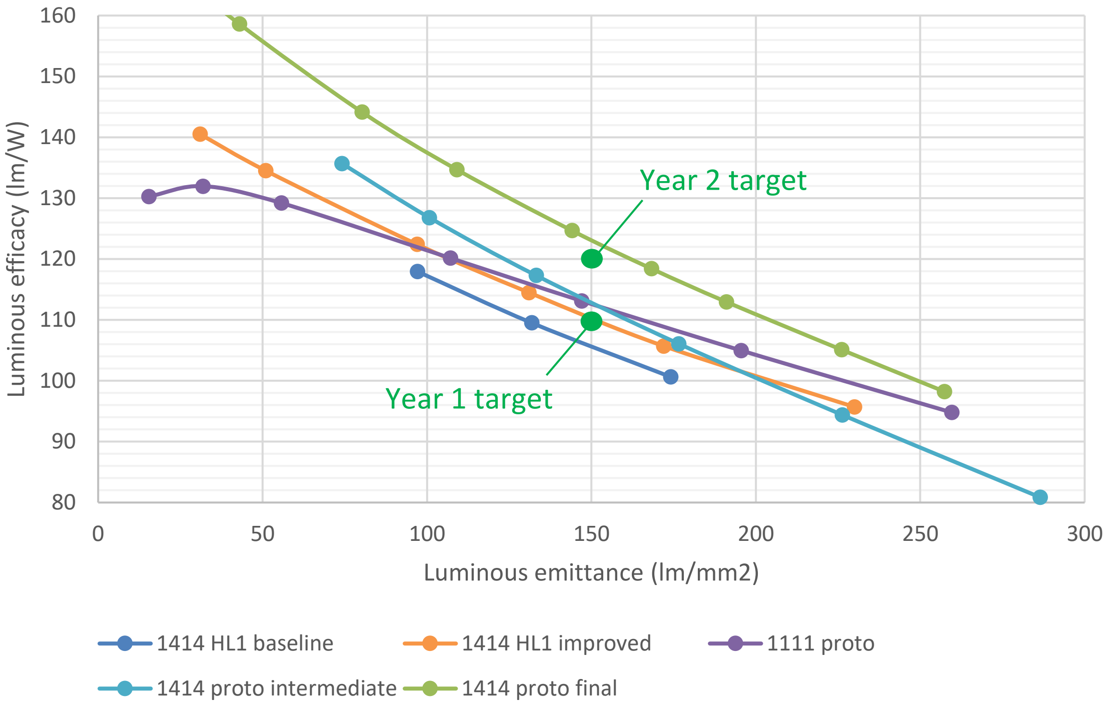

Figure 13: LED-level luminous efficacy vs. emittance of devices with baseline package architecture: production samples (1414 HL1 baseline) and samples with Year 1 epi and die improvements included (1414 HL1 improved). All data measured at T_j = 85 °C.

PCBs were designed and fabricated to accommodate 21 of the 1414 prototype LEDs at a pitch of 1.5 mm, i.e. with a nominal edge-to-edge spacing of 100 µm between the LEDs. In order to make the PCBs suitable for both white and RGB tunable arrays, the 21 LEDs are arranged in three separately addressable strings of 7 LEDs each.

Three fixed white LED modules were built on these boards with the LEDs from the final performance demonstration build. Photometric measurements were conducted on all three boards at a junction temperature of 85 °C and currents from 10 mA to 700 mA in each of the three strings. For the purpose of determining the emittance, the source size is taken to be the total area of the LEDs including the spacing between them, i.e. 21 x 1.5 x 1.5 mm^2 = 47.25 mm^2. Figure 14 shows the average efficacy vs. emittance of the three final demonstration modules. At the benchmark emittance of 80 lm/mm^2, the average efficacy is 135 lm/W, surpassing the 128 lm/W project target. The average CRI Ra is 80.7 at a CCT of 3884 K and Duv = +0.004.

To confirm that the cross-talk between adjacent LEDs in the dense packing configuration is acceptable, we plot the measured color points of the LEDs and the modules in Figure 15. As this comparison shows, the modules have a slightly higher v' coordinate than the LEDs by about 0.001 to 0.002 points due to additional phosphor conversion. This is consistent with our earlier observations and expected to be well within acceptability limits for practical products.

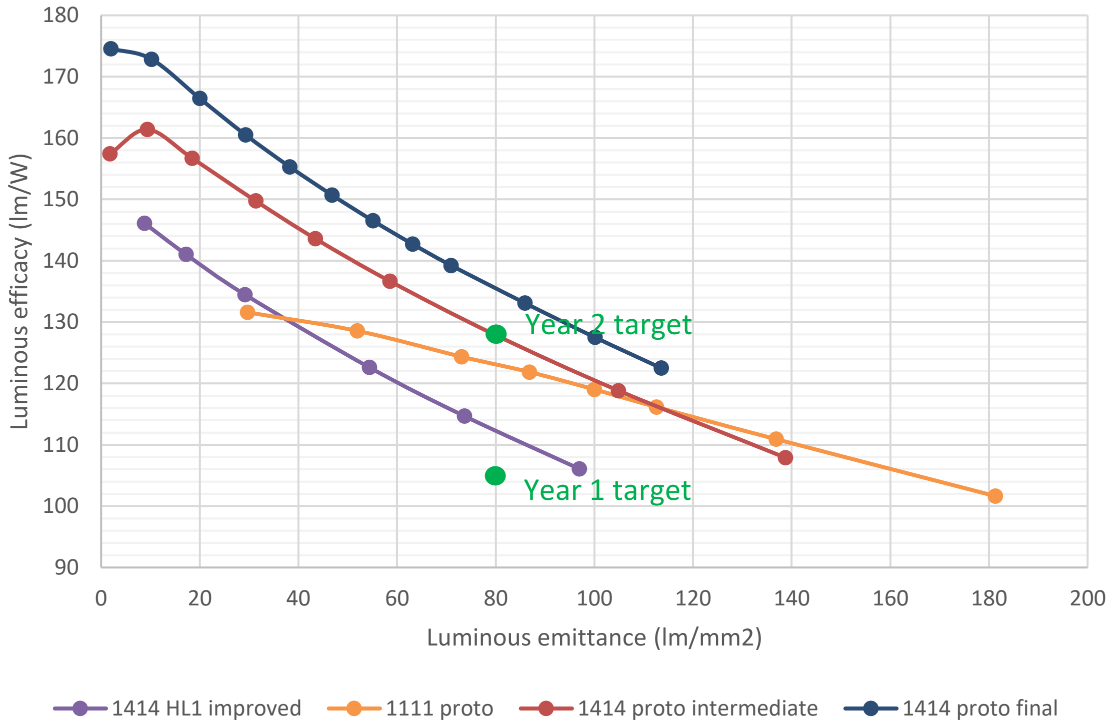

Figure 14: Module-level luminous efficacy vs. emittance of densely packed HL LED arrays: 1414 prototype device architecture with project-end epi and die improvements (1414 proto final) compared with earlier performance demonstrations (see Figure 9). All data measured at T_j = 85 °C.

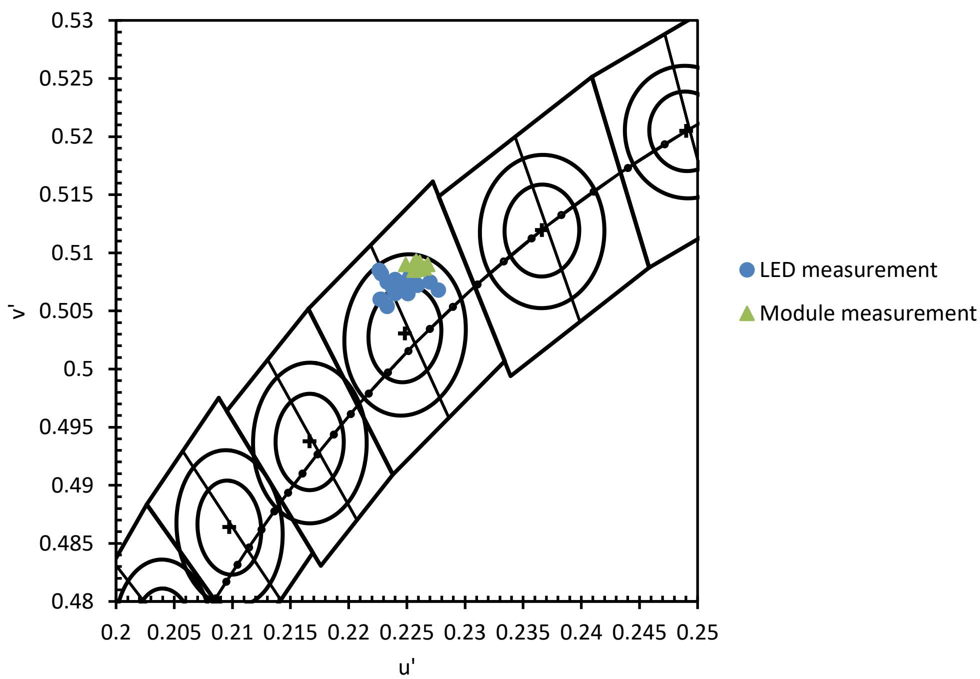

Figure 15: Chromaticity of 4000K high-luminance LEDs from final demonstration build measured as individual LEDs and assembled in densely packed modules. All data measured at a drive current per LED of 350 mA and junction temperature of 85 °C.

Five tunable CCT modules were built on the same PCB with the phosphor-converted red, green and blue LEDs from the final performance demonstration build (Figure 16). Photometric characterization was done on each of the modules at a junction temperature of 85 °C and currents from 10 to 700 mA on each of the red, green and blue LED strings as shown in Figure 17.

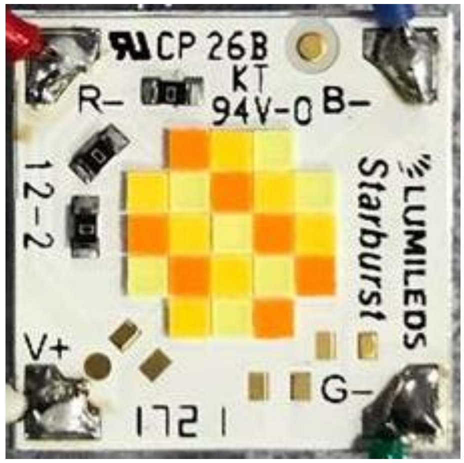

Figure 16: Tunable CCT demonstration module. The 1414 prototype LEDs are assembled at a pitch of 1.5 mm.

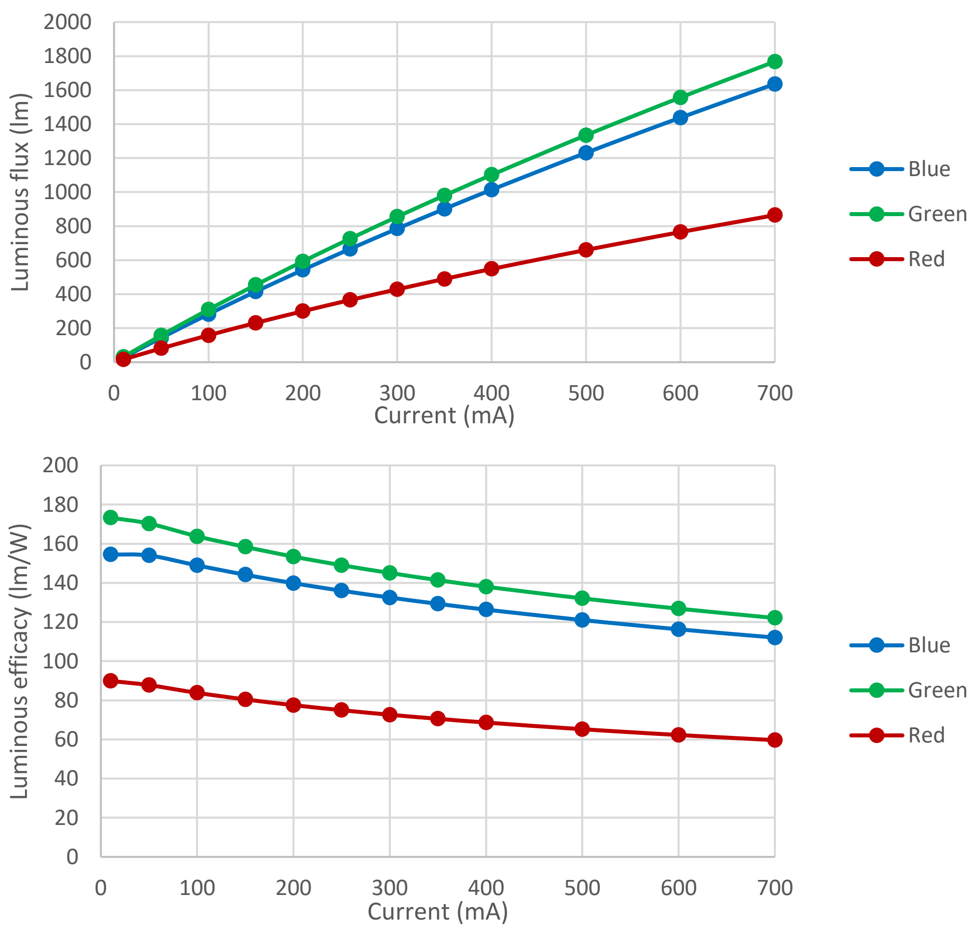

Figure 17: Luminous flux (top) and efficacy (bottom) of tunable CCT demonstration modules. All data measured at T_j = 85 °C and reported as average of 5 modules.

To calculate the performance of the modules at the benchmark conditions, we first calculate the total flux needed to achieve an emittance of 80 lm/mm^2. With a total source area of 47.25 mm^2, this total flux is 3780 lm. From the measured color points of the red, green and blue LED strings, we can then calculate the required luminous flux of the three colors to hit the color target of 4000K, as shown in Table 1. Subsequently, we can determine the current and voltage in each of the channels to produce these respective luminous flux values, and thereby the total power in the module. This leads to a luminous efficacy of 105 lm/W, exactly meeting the project target. The color rendering index at these conditions is CRI Ra = 93.4.

Table 1: Drive conditions of blue, green and red LED strings required to produce 3780 lm at 4000K.

	Blue	Green	Red	Total
Flux (lm)	1002	2227	551	3780
If (mA)	395	950	402	
Vf (V)	20.05	21.26	19.98	
P (W)	7.91	20.20	8.03	36.14
Efficacy (lm/W)	**127**	**110**	**69**	**105**

These performance demonstrations conclude the activities for this project. In summary, we have developed and demonstrated a high-luminance LED device that improves the tradeoff between efficacy and emittance both at LED level and module level. Two paths were explored: one in which the package size was reduced to facilitate closer packing at the expense of a slight efficacy penalty; and one in which the package size is retained and the package architecture was optimized for increased light extraction. The latter was found to be more suitable for illumination applications due to its higher efficacy at relevant emittance and the lower component count and cost. These project results will help develop and commercialize high-luminance LED products that improve the performance and reduce the energy consumption of directional lighting applications.