FINAL REPORT FOR DE-FC26-05NT42342
An Efficient LED System-in-Module for General Lighting Applications
Philips Lighting - Lighting Electronics North America

This document consists of four sections. Section I describes the accomplishments of the project. Section II covers the milestones, giving status with respect to the original plans. Section III lists the documentation produced in the project. Section IV describes the organizations involved in the work.

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I. ACCOMPLISHMENTS

The objective of the project was to realize an LED-based lighting technology platform for general illumination, starting with LED chips, and integrating the necessary technologies to make compact, user-friendly, high-efficiency, energy-saving sources of controlled white (or variable-colored) light. The project is to build the system around the LEDs, and not to work on the LEDs themselves, in order that working products can be introduced soon after the LEDs reach suitable efficiency for mass-production of high-power light sources for general illumination. Because the light sources are intended for general illumination, color must be accurately maintained, requiring feedback control in the electronics.

The project objective has been realized and screw base demonstrators, based on the technology developed in the project, have been built, two of which were delivered to the DOE.

Fig. 1 shows a diagram of the demonstrator. Fig. 2 is a photo of the final demonstrator, disassembled to display the components. The maximum outer diameter of the demonstrator is 4.7 inches, slightly less than the diameter of a PAR38 lamp. The length is 5.5 inches, which is less than the maximum length (6”) for a standard PAR38 lamp. This demonstrator is the culmination of three phases of work, each of which generated at least one set of demonstrators. This final report will focus primarily on the results with the final demonstrator and not cover details of intermediate results leading up to it.

The demonstrator has been designed with the characteristics:

• RGBW LEDs for full color variability, including controlled white colors.
• Color control with temperature feedforward and flux feedback. Flux feedback is implemented with an unfiltered photodiode. The electronic control system uses PWM to drive the LEDs, and, at certain points in the cycle, each individual LED color is on alone and a measurement of its flux is made. A background measurement, with no LEDs on, is also made, and used to correct the flux readings for background light. Temperature feedforward is implemented with a thermal sensor mounted on the LED MCPCB.

• Wireless interface, capable of handling multiple LED-SIMs
• Two current levels, for accurate deep dimming.
• Edison base
• 50,000 hour lifetime
• PAR38 size
• Flood light distribution
• CRI and Flux maximization options
• Daylight compensation

The project originally started with the goal of using RGB and Amber LEDs, but the light output of Amber LEDs is so poor at elevated temperatures that we made the change to RGBW LEDs. This change comes at a cost to the CRI, but yields significantly higher flux at normal operating temperatures.

**Efficiency**

Fig. 3 shows the efficiency of the DC-DC controller, which is above 90% for output voltages above 20V. This was measured without the wireless control daughter pcb, and the microprocessor was forced into standby. Fig. 4 shows the efficiency of the AC-DC electronics, which is above 92% for most conditions when power output is between 10 and 25 Watts. The losses from the wireless daughter pcb, the microprocessor and standby power for the rest of the electronics were determined by measuring the power supplied to the DC-DC electronics when the LED currents were turned off (0.73 Watts). The efficiency of the optical reflector is shown in Fig. 5. Extensive optical modeling was done to produce the Phase 2 TIR optic, which was measured to be 97% efficient. However, a diffuser is required to reduce spatial color variation. The diffuser reduces the optical system efficiency to 92%. Changes were made to the reflector in Phase 3 which reduced the optical efficiency. First, “feet” were added to fit around the LEDs. These feet result in loss of the low angle light from the LEDs. Secondly, the silicone that we were using to fill the cavity in the reflector surrounding the LEDs was found to turn brown in the vicinity of the hottest LEDs (B), after extended operation, and to cause degradation of the phosphor in the white LEDs. The Phase 2 silicone had a refractive index of 1.5. We changed to a silicone with refractive index of 1.4 to solve these problems. If a subsequent product development cycle were done, we would eliminate the feet on the reflector, which were no longer necessary after the silicone was changed and our process for filling the cavity with the silicone was changed. The goal of the project was to obtain above 70%, not including the AC-DC electronics, which has been exceeded. Combining all of the losses above, including the AC-DC, the system efficiency is 66%. If we returned to the Phase 2 optic design, system efficiency could improve to 73%. Other improvements, such as integrating the diffuser with the reflector, to remove air/plastic interface losses, or
changing the AC-DC electronics to a resonant topology, would increase efficiency further.

**Efficacy**
The light output of the demonstrator (Fig. 6) is a maximum of about 650 lm after allowing the temperature of the unit to stabilize. The goal of the project was to reach 1300 lumens. This goal was based on using LEDs with an average efficacy of over 100 lm/W. The efficacy of the entire system (shown in Fig. 7) is low; its maximum is 35 lm/W at a setpoint of 4000K. The measured flux from the LEDs is low with respect to that foreseen in the proposal. The flux per LED is 47.3, 40.5, 18.4 and 145.5 lumens/LED, for R, G, B and W, respectively. Note that the LED current is 350 mA for R and G and 700 mA for B and W. The efficacy of the white LEDs is about 85 lm/W. As a result of the relatively low LED efficacies with respect to the proposal, the light output and system efficacy are low. The system efficacy (Fig. 7) reaches a maximum of about 35 lm/W at 4000K. If the LEDs were all replaced with W LEDs having the same efficacy as the W LEDs in the demonstrator, then the luminous flux would be 1310 lumens, meeting the original goal. If all LEDs had an average efficacy of 100 lm/W, then the overall system efficacy would improve to 66-73 lm/W, depending on the optics efficiency, as described in the previous section.

**Color control**
Excellent color control has been obtained using a control system involving temperature feedforward and flux feedback. Calibration of the lamp is required to determine the temperature-dependent coefficients and the initial fluxes for each LED color. Because four LED colors are available, an infinite number of combinations of lumen fractions of the individual LED colors can reach a user-specified CCT, in general. This additional degree of freedom can be used to optimize lamp performance in some way. The software algorithm allows selection of two modes. The possibilities include maximization of the flux (FluxMax algorithm) and maximization of the CRI (CRImax algorithm). The algorithm can perform CRI maximization only for setpoints between 2700 and 6500K, on or close to the Planckian locus. Outside of this range, the control algorithm defaults to Flux maximization.

Operation of modules with optimized and non-optimized selection of LED spectral properties shows that, if LED spectral parameters are selected for high CRI, then the difference between the luminous flux and CRI for CRI maximization and Flux maximization are small. If the LED spectral parameters are not close to those required for high CRI, then the two algorithms produce much larger differences in luminous flux and CRI. The data shown below, for the Phase 3 demonstrators, was all measured with LEDs having spectral properties selected for high CRI.

Color error, defined as \( \Delta uv = \sqrt{(u-u_t)^2+(v-v_t)^2} \), where \((u_t, v_t)\) is the target color set by the user, has been measured for various operating conditions. It has been measured as a function of heatsink temperature, primarily for color setpoints and intensities on the Planckian locus, for operation with both CRI maximization and flux maximization. The color error, \( \Delta uv \), is consistently below 0.002. The color error data presented in Figs. 8-10
and 12-17 was all measured on a single unit (one of the two units delivered to the DOE at the conclusion of the project). We have also measured color error for setpoints off the locus (Fig. 18). Color error has been measured as a function of time for a unit that has been operating for more than a year (Fig. 19).

The color error for the two Phase 3 units delivered to the DOE at the end of the project was less than 0.002 when they were operated at full load (Fig. 8), for both CRImax and FluxMax operation. The color error is also less than 0.002 when operated with the intensity dimmed to the point that the maximum duty cycle is 10% (Fig. 9). The color error is also low when the unit is operated in the low current mode (Fig. 10), near maximum duty cycle (maximum duty cycle about 85%). This is accomplished by dropping the target intensity until the maximum duty cycle falls below 6%, at which point the software triggers the unit to enter the low current mode. Then, the target intensity is increased until the duty cycle is near 85%. Measurements were made at 85%, because, if a duty cycle exceeds 88%, then the software will trigger the unit to enter the high current mode. A schematic view of system operation with two current levels is shown in Fig. 11. Some hysteresis is required to avoid excessive switching between the two current levels.

The measured CRI is given in Figs. 12-14. The CRI is consistently between 85 and 90 for CCT setpoints of 4000, 5000 and 6000K. It drops for 3000 and 9000K, where only three LED colors are used to reach the setpoint. Data is given for the same operating conditions as in the previous paragraph. As described above, the difference between CRImax and FluxMax is small when the LED parameters are chosen to yield high CRI. As a counterexample, the 6000K CRI measured on a Phase 1 demonstrator, for which LED parameters were not optimized, was 78 with FluxMax operation and 88 with CRImax operation.

The luminous flux output of the lamp, corresponding to FluxMax and CRImax operation, is shown in Figs. 15-17. There is a small decrease in flux for CRImax operation, with respect to FluxMax operation. Data is given for the same operating conditions as in the previous two paragraphs.

In addition to the extensive characterization of module performance along the Planckian locus, we also measured color error for an array of setpoints spanning the entire color triangle (Fig. 18). The color error was measured at a single heatsink temperature at each point. All color errors were less than 0.003.

The change of color error with time is being monitored for a Phase 1 lamp (Fig. 19). The test has run for nearly 12000 hours. The color error remains below 0.003. However, the color errors appear to be steadily moving away from the blue primary. Several blue LEDs from the batch used to make the Phase 1 demonstrators have failed in other testing. The color error trends in Fig. 19 may be a result of deterioration in the B LED that is not detected by the control system (worsening of the thermal resistance, for instance). Further study, with a larger number of units and variety in LEDs is required to make more firm conclusions.
**Daylighting**

Because the LED-SIM contains optical sensors, implementation of daylighting compensation schemes without the need for additional hardware is possible. The LED-SIM flux measurement algorithm includes the measurement of a background signal. This background measurement, with proper calibration, can be used to perform daylight compensation. The LED-SIM software was changed to enable daylight compensation, and measurements were performed with two different sources of background light. The LED-SIM was placed in an integrating sphere. Background light was generated by either an incandescent lamp or an array of cool-white phosphor-converted LEDs. The background signal was calibrated with respect to the LED-SIM photodiode reading, and calibration parameters were stored in the LED-SIM software. The LED-SIM was then turned on and the current to the background lamp was varied. Spectra, fluxes, CCTs and LED-SIM microprocessor parameters were measured. Fig. 20 shows the results for an incandescent background source. The software automatically dims the LED-SIM in response to increasing background light until a minimum intensity is reached (5% in the case of these measurements). The total flux is constant within about 10%, if the first and last points are disregarded. The total spectrum transitions smoothly from the SSL spectrum to the incandescent spectrum as the current to the incandescent lamp increases and the LED-SIM dims.

The upturn of the total flux in Figs. 20 (top) occurs when the flux of the background light source begins to exceed the specified total flux and the SSL module can no longer compensate. (No negative light output is possible from the SSL module!) The sudden changes in total flux when the background lamps are first turned on is harder to explain. In the case of the incandescent background lamp, the large amount of infrared light may be playing a role.

For each of the daylighting measurements, calibration of the photodiode response to the background light source is required. We used a quadratic fit of the luminous flux vs. photodiode background signal, for the incandescent background lamp, and a linear fit for the white LED background lamp. The response is very different for the two light sources that we used. Because of the high amount of infrared light in the incandescent source, the photodiode voltages for a given flux of visible light were much higher than the corresponding photodiode voltages for the same flux of white LED light. This indicates that any application of these lamps for daylighting will require calibration after installation (actually this is a requirement for any daylighting installation.) It could also be that the compensation will vary somewhat if the spectrum of the daylight varies (e.g. cloudy/sunny or time of day). The extent of this variation goes beyond the scope of this project.

The change in color temperature was also monitored and is presented in Fig. 20 (middle). The SSL module was set to 4500K during the measurements. The LED-SIM is not able to determine the color of the background light and compensates only for the background luminous flux variation. Therefore a gradual transition from the color temperature of the SSL module to the color temperature of the background light source is observed. For the
white LED and incandescent background lamps, the final color temperatures are near 6000K and 2500K, respectively, which are typical color temperatures for these light sources.

**IC design**

A major portion of the project was to design and build an ASIC to simplify and shrink the electronics. Together with colleagues at NXP, we developed a strong specification for the IC, which integrates the driver circuitry, portions of the sensing circuitry and portions of the control circuitry. The ASIC also provides an I²C communication system. The electronics system was partitioned with a separate off-the-shelf microcontroller in addition to the ASIC. We considered integrating the microcontroller into the ASIC, but a separate microcontroller enables greater flexibility and a wider range of applications. In the future, when large-volume applications become a reality, integration of the microprocessor with the ASIC functionality is likely to become desirable. The ASIC specification includes some of the control functions, such as generation of the PWM signals, which makes it possible to use a less-complicated microcontroller, (or frees the microcontroller to perform other tasks, such as wireless communications). A single microcontroller can be used to control multiple ASIC’s in a master/slave configuration – a feature that we are made use of in the Phase 2 demonstrator, because it contains two ASICs and only one microcontroller.

Two silicon runs were performed. First silicon was finished in September of 2006. There were problems with the ASIC, including interference between the I²C communications and power circuitry and higher current in portions of chip than expected, which led to failures. Several versions of first ASIC were made subsequently with modifications that did not require new silicon. Of these, some are more stable than others. A stable version was used to make the Phase 2 modules. Second silicon was finished in April 2007. There were still problems in the analog circuitry. All were ultimately solved, but NXP (our silicon partner, which was part of Philips at the start of the project) decided to simplify the specification in the interest of addressing a larger market, sooner. NXP was proceeding with plans to produce the simplified ASIC, but recently decided to place the product on hold. As a result of NXP’s decision to simplify the ASIC, the Phase 3 demonstrator is made without the ASIC. Discrete off-the-shelf components have improved so that we were still able to meet the size requirements (Fig. 2).

In the proposal, we also discussed mounting LED die directly on silicon, which could also have some electronics integrated into it. Ultimately, we decided not to integrate any of the electronics in the submount upon which the LEDs are mounted. The LED industry is moving away from silicon submounts toward ceramic submounts (such as those used in the Lumileds Flash and Rebel LEDs). In addition, space in SSL demonstrators is limited more by heatsink and optics volume than by electronics, making it unnecessary to miniaturize the electronics to such an extent that they are integrated into the high-temperature, high-light-background environment of the submount, through which all of the LED heat must be conducted. Another disadvantage of using a silicon submount for multiple LED die, with integrated electronics, is that most of the silicon area would be occupied by the large pads for the LED contacts. Any integrated electronics would
occupy a relatively small area. The price of the silicon would therefore be high, because of the large size of silicon with a very low density of circuitry.

In contrast to the original plans, the ASIC developed in Phases 1 and 2 was not used in Phase 3, because of NXP’s decision not to further pursue the ASIC specification produced in Phases 1 and 2. The uncertain availability of ASICs caused us to redesign the electronics using off-the-shelf parts, including a newly available IC, intended for driving LEDs. This IC does not have nearly the features in our original ASIC specification, but did allow us to make the electronics more compact than they otherwise would have been. Because the IC can operate at higher voltages than the ASIC, we were also able to run the LEDs with two strings of LEDs instead of four strings. The features that were not available were implemented with other electronics and software.

Optics
The optical reflectors were designed using commercially available ray-tracing software. The chosen reflector is a facetted TIR reflector. Three generations of reflectors were built and characterized. Fig. 21 shows the intensity and color variation measured as a function of angle from the optic axis of the Phase 3 reflector. Addition of a diffuser at the reflector output aperture is required to bring the spatial color variation below 0.002 for the angles where intensity exceeds 10% of the maximum intensity (Fig. 21). The measured spatial color error is below the specified color error from the project proposal. Because we are using Lumileds’ Rebel and camera flash LEDs, which are mounted on AlN or Al₂O₃ submounts, the minimum spacing between LEDs is relatively large. Better color mixing can be expected if the LED die spacing is smaller and the input aperture of the reflector is more completely filled. In the future, availability of smaller-footprint LED packages may allow closer packing of the LED, better filling of the reflector input aperture, and better color uniformity. (Or similar color uniformity with less diffusion.)

The efficiency of the Phase 2 reflector is about 92% (Fig. 7). Efficiency of the Phase 3 reflector is lower, only 83%, for two reasons. For the second and third reflector designs, the base of the reflector was modified, adding “feet” to allow it to fit around the LEDs. However, low angle light is lost by the addition of the feet. Recovery of this portion of the losses is possible, because the feet are actually no longer required. Changes in the silicone material used and to the process for filling the LED cavity with silicone, as well as the method for mounting the optic to the heatsink have made the feet unnecessary. The second reason involves the choice of silicone used to fill the cavity in the reflector that fits around the LEDs.

We have done extensive experimentation with silicone filling of the space around the LEDs. The main challenge is to avoid the formation of bubbles in the silicone that are in the optical path and to use a silicone that does not degrade, or cause degradation to the LEDs. The silicone coefficient of thermal expansion is considerably larger than that of the other components in the light source, so expansion and contraction of the silicone during warming and cooling of the LED-SIM is unavoidable. The approach that we have settled on is to fill the cavity in the reflector with a silicone that is hard enough that bubbles don’t easily migrate into the optical path, yet soft enough that the reflector can be
pushed down onto the LEDs and the silicone will deform and fill the space around the LEDs. Gaps were left between the MCPCB and the reflector to allow for expansion of the silicone. The assembly process should be readily manufacturable. It is much simpler than processes involving gluing the reflector to the MCPCB and then injecting silicone from the back side of the MCPCB through injection holes. We first used silicone with a refractive index of 1.545. However, operation of light sources for many weeks or months resulted in the degradation (browning) of the silicone near the hottest LEDs (B) and in degradation (browning) of the phosphor in the white phosphor LEDs. Eventually we changed to a silicone with refractive index 1.4, which eliminated these problems. However, lower refractive index will reduce the optical efficiency.

**Thermal design**

Based on input from the DOE at our Phase 1 budget review, we stopped the Phase 1 efforts on active cooling and limited our thermal design to passive cooling. Active cooling is expected to be too expensive, and to introduce reliability issues. Our designs keep junction temperatures below the maximum temperature specified for 50,000 hour lifetime. Designing for 50,000 hour lifetime has become easier during the course of the project, because LED manufacturers have increased the maximum junction temperature required for 50,000 hour lifetime. Despite this increase, it remains desirable to keep the junction temperature, particularly of the red LEDs, as low as possible to avoid the decrease in LED efficacy that occurs as temperature increases.

The thermal design for our Phase 3 demonstrator maintains LED junction temperature below 135°C for B, G and W LEDs (B and W at 700mA, G at 350mA), and below 110°C for R LEDs (at 350mA), in an ambient of 40°C or below, with 21.5W of power dissipated in the LEDs, and for worst-case orientation of the LED-SIM. (Fig. 22) The calculated temperatures are low enough to meet Lumileds specifications for lifetime of at least 50,000 hours.

**User interface**

The user interface software provides several options for LED-SIM control to the user. Both wired and wireless communications have been developed. The demonstrators delivered to the DOE have wireless interfaces. The units are controlled from a handheld PC, with a USB dongle for the wireless transmissions. The wireless system uses a protocol named “Embernnet” which is a precursor for Zigbee. Embernet allows new commands to be defined, which we have done for color commands. The Zigbee standards for color commands are not yet finalized.

The graphical user interface (GUI) allows the user to select preset colors, such as red, green, blue and three CCTs on the Plankian locus (buttons on left side of Fig. 23). He can select white of a particular CCT (with the slider at the bottom of Fig. 23). He can select colors, including whites, by clicking inside the color triangle. In addition, we have produced pre-programmed modes that take advantage of the dynamic ability to control the color. The modes include: 1) Saturated colors, where the selected color setpoint walks slowly around the outside of the color triangle, 2) “Walkthrough”, where the color point
walks along straight lines inside the triangle, bouncing back when it encounters an edge, and 3) “Fireplace”, where the color setpoint and intensity are randomly varied to represent the light that would be produced by a fireplace in a room. Mode 3 is most effective if several lamps are operating simultaneously, to produce spatial variation in light color and intensity, in addition to temporal variation.

Additional controls are present in the software for the wireless interface (Fig. 24). If a wireless interface is being used, the user must first click on the “Configure LED Spot” button (Fig. 23), which brings up the Configuration Panel of Fig. 24 (top). The system will automatically search for wireless units and will show the list of available unit addresses in the central window. The user selects one of the available addresses, and then clicks in the LED GUI to select parameters for that lamp. To change to another LED-SIM, a new address must first be selected in the Configuration Panel.

The wireless control system also has options to cluster LED-SIMs into groups, which can be simultaneously controlled with a single command, and to broadcast commands to all units. There are also options to read out internal parameters of the LED-SIM, such as heatsink temperature, photodiode signals and duty cycles. Clustering of the LED-SIMs into groups is accomplished with the Commissioning Panel (Fig. 24 (bottom)), which is accessed by selecting “Config ID” from the Configuration Panel.

We have measured EMI from the units. They pass the FCC-A requirements and nearly pass the FCC-B requirements (Figs. 25 and 26). We expect that minor changes to inductor and capacitor values will be sufficient to pass FCC-B.

The results of this project have been used to help launch a new color tunable product, LEXEL DLM (Fig. 27). The product was announced at the Light and Building show in Frankfurt, Germany in 2008.

II. Milestones and Deliverables

The project milestones and tasks are shown below. All were completed. Some tasks had to be repeated, because of changes in the project. For instance, the ASIC designed in Phases 1 and 2 was not available for Phase 3, which necessitated a redesign of the DC-DC electronics. The optical reflector was also redesigned twice. Other changes included using WRGB LEDs instead of the originally planned RAGB LEDs, and using Rebel and Camera Flash LEDs, as these advances in LEDs were made, instead of mounting bare LED die on a common submount.

Phase 1: Intermediate LED-SIM with RAGB LEDs

<table>
<thead>
<tr>
<th>Task Description</th>
<th>Status</th>
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<tbody>
<tr>
<td>1.1 Phase 1 electronics architecture evaluation</td>
<td>Done</td>
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<tr>
<td>1.2 Thermomechanical design &amp; modeling</td>
<td>Done</td>
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<tr>
<td>1.3 Optical modeling and design</td>
<td>Done</td>
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<tr>
<td>1.4 Construct optical prototypes</td>
<td>Done (in Phases 2&amp;3)</td>
</tr>
<tr>
<td>1.5 Design drivers/software for Phase 1</td>
<td>Done</td>
</tr>
<tr>
<td>1.6 Build driver/control prototype</td>
<td>Done</td>
</tr>
</tbody>
</table>
1.7 Silicon integration and testing  Done
1.8 Construct & test Phase 1 LED-SIM  Done
1.9 Design/build Phase II driver prototype  Done

**Phase 2: Final LED-SIM**

2.1 Test LED-SIM  Done
2.2 Optical modeling and design  Done
2.3 Thermomechanical modeling and design  Done
2.4 Finalize electronics design  Done (but redone in Phase 3)
2.5 Design user interface  Done
2.6 Silicon integration  Done
2.7 Construct final LED-SIM  Done

**Phase 3: Build flood lamp prototypes**

3.1 Test LED-SIM  Done
3.2 Design portions external to LED-SIM  Done
3.3 Construct prototype flood lamps  Done
3.4 Test lamps  Done

The original project deliverables were:

1. An LED-SIM-based demonstrator providing:
   - Lumen output (at 3000K) near to that of a 90W Halogen PAR38.
   - CRI of >90
   - Controllable light (color and intensity)
   - Intuitive user interface

2. Technical progress reports (Federal Assistance Reporting Checklist) documenting:
   - Work performed in the three project phases
   - Progress in the component technologies (optics, thermal management, electronics, and silicon integration)

Two LED-SIM based demonstrators, with Edison-base sockets, a handheld controller, wireless transmitters, and wooden bases were delivered to the DOE. With respect to the deliverable goals, the lumen output is low, reaching a maximum of 600-700 lumens, as described above. This is only about half the amount required to be comparable to a 90W PAR38. The CRI is slightly lower than the original deliverable specification, falling between 85 and 90 over most of the Plankian locus between 2700 and 6500K. The deliverables exceeded the specifications for color error, and spatial color uniformity. In addition, the LED-SIMs are fully wirelessly controlled. The reports have all been delivered, with this report constituting the final deliverable.

**III. Documentation**

The documentation produced during the course of the project includes:

*Patent Disclosures:*

“High Color-Rendering-Index LED Lighting Source using LEDs from multiple wavelength bins”
“Power management during operation of LED light sources”
“Color control strategy for multicolored LED modules”
“Algorithm for LED light source control”
“Daylighting control of LED lamps”
“Flexible & efficient communication protocol for small embedded processors”
“Improved Optical Connection between LEDs and Secondary Optics “
Still to be completed: 1. CW-WW color mixing for accurate color control along the Planckian locus, 2 Use of tapped inductors for increased efficiency AC-DC power supply


Proprietary document: IC specification

Presentations:

IV. Participants

Below is a list of the organizations, other than Philips Lighting Electronics, involved in the project, with a summary of their involvement. NXP is the only organization that was part of the project. The others supplied either components or technology.

NXP – Involved in IC specification and production of ASICs for the silicon integration tasks.
Best Proto – Performed PCB assembly of driver electronics for Phases 2 and 3.
NuSil – Interacted with us to select appropriate silicone materials. Provided those materials for testing and for use in the demonstrators.
Lumileds – Provided LEDs, including Rebels and custom made camera flash LEDs.
Philips Lighting (NL) – We shared knowhow on color control software.
LPI – Performed injection molding to produce optical reflectors according to our specifications.
Philips Equos project – We obtained hardware & some of the software necessary to do the wireless interfacing with the LED-SIM from this project. We adapted their hardware and software, intended for use in dimming of fluorescent lamps, for use with the LED-SIM.
Philips Research – The initial ideas for the original project proposal were based on work done originally at Philips Research in Briarcliff Manor, NY.

There were many other contributors to the project, who played lesser roles, including the PCB maker, MCPCB maker, the company that machined the heatsinks, and suppliers of various electronic and non-electronic components.
Fig. 1: Exploded drawing of Phase 3 demonstrator. The diffuser on the output aperture and the metal screw portion of the Edison base are not shown.
Fig. 2: Photographs of Phase 3 demonstrator, disassembled (top) and assembled (right). The diffuser is not present in the disassembled photo, but fits between the exit aperture of the transparent plastic reflector and the retaining ring.
Fig. 3: Efficiency of DC-DC electronics under various load conditions. The efficiency is above 90% when the load voltage is above 20V. The figure gives a sense of how efficiency depends on the selection of PFET and free-wheel diode in the hysteretic buck controller used to control LED current.
Fig. 4: Efficiency of AC-DC supply for different input AC voltages. The efficiency is between 92 and 93% over most of the range from 10-25 Watts of output power. The supply is neither isolated nor power-factor corrected, to keep electronics volume and efficiency high.
### Efficiency of optical system

The optics of Phase 2 and 3 are compared.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Phase 2</th>
<th>Phase 3</th>
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<tbody>
<tr>
<td>R and W Rebel LEDs on MCPCB, without reflectors:</td>
<td>257.9 lm</td>
<td>582</td>
</tr>
<tr>
<td>Add optical reflector and silicone:</td>
<td>254.2 lm</td>
<td>546</td>
</tr>
<tr>
<td>Cover the base of the reflector:</td>
<td>250.7 lm</td>
<td>521</td>
</tr>
<tr>
<td>Efficiency of reflector alone:</td>
<td>97.2%</td>
<td>90</td>
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<tr>
<td>R and W Rebel LEDs with reflector, cover &amp; diffuser:</td>
<td>237.2 lm</td>
<td>479</td>
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<tr>
<td>Efficiency of reflector with diffuser:</td>
<td>92.0%</td>
<td>82.3</td>
</tr>
</tbody>
</table>

Efficiency of optic is lower than Phase 2 optic. Reasons: “Feet” added at base. Lower refractive index silicone.

†The Phase 3 values were measured with W only.

**Fig. 5:** Efficiency of optical system. The optics of Phase 2 and 3 are compared.
Fig. 6: Light output from a Phase 3 demonstrator, for various color setpoints (CCTs) and various intensities, as well as for Flux and CRI maximization. The requested intensity was varied to make the maximum duty cycle be 90%, 50%, 20% or 10% in the high current setting, and 85% and 50% in the low current setting. The low current setting is about 1/8 of the high current setting.
Fig. 7: Efficacy of a Phase 3 demonstrator, for various color setpoints (CCTs) and various intensities, as well as for Flux and CRI maximization. The requested intensity was varied to make the maximum duty cycle be 90%, 50%, 20% or 10% in the high current setting, and 85% and 50% in the low current setting. The low current setting is about 1/8 of the high current setting.
Fig. 8: Performance of a Phase 3 demonstrator operating at full output (maximum duty cycle 90%) in closed loop operation with (top) Flux maximization and (bottom) CRI maximization. Heatsink temperature was varied with a power resistor mounted to the heatsink. The color error remained below 0.002 for all conditions. The openloop measurements are from a Phase 1 unit operated without feedforward or feedback and are given for comparison. Note that the results for 9000K are for Flux maximization operation in both cases, because CRI_max operation defaults to FluxMax operation for setpoints outside 2700 – 6500K.
Fig. 9: Performance of a Phase 3 demonstrator operating in closed loop operation with (top) Flux maximization and (bottom) CRI maximization. The target intensity was reduced with respect to Fig. xxx, to the point that the maximum duty cycle was 10%. The LED current is at the high level.
Fig. 10: Performance of a Phase 3 demonstrator operating in closed loop operation with (top) Flux maximization and (bottom) CRI maximization. The unit was operating with in the low current mode, with a maximum duty cycle near 85%.
Fig. 11: Desired duty cycle behaviour as target flux varies, for a system with two current values. As target flux drops from its maximum, a point is reached when the maximum duty cycle drops below a trigger (10% in the example above). At this point (indicated by an upward arrow), the source switches to the low current level and duty cycles increase correspondingly. As the target flux is increased from its minimum, a point is reached when the maximum duty cycle exceeds a certain trigger (80% in the example above). At this point (indicated by the downward arrow) the source switches to the high current level and duty cycles decrease correspondingly. In order to avoid jumping back and forth between the two levels for targets near the transition points, the current step and the trigger points must be chosen to allow a hysteresis window, as shown in the figure.
Fig. 12: CRI for a Phase 3 demonstrator operating at full output (maximum duty cycle 90%) in closed loop operation with (top) Flux maximization and (bottom) CRI maximization. Note that the results for 9000K are for Flux maximization operation in both cases, because CRImax operation defaults to FluxMax operation for setpoints outside 2700 – 6500K. As explained in the text, the selection of LEDs is such that the difference between CRI maximization and Flux maximization is small.
Fig. 13: CRI for a Phase 3 demonstrator dimmed to the point that the maximum duty cycle is 10%. The unit is operating in closed loop operation with (top) Flux maximization and (bottom) CRI maximization.
Fig. 14: CRI for a Phase 3 demonstrator operating in the low current mode, with a maximum duty cycle of about 85%. The unit is operating in closed loop operation with (top) Flux maximization and (bottom) CRI maximization.
Fig. 15: Luminous flux corresponding to the CRI measurements in Fig. 8 and 12 above. The unit was operating at full output (maximum duty cycle 90%) in closed loop operation with (top) Flux maximization and (bottom) CRI maximization.
Fig. 16: Luminous flux corresponding to the CRI measurements in Fig. 9 and 13 above. The unit was dimmed to yield a maximum duty cycle of 10% in closed loop operation with (top) Flux maximization and (bottom) CRI maximization.
Fig. 17: Luminous flux corresponding to the CRI measurements in Fig. 10 and 14 above. The unit was operating in the low current mode, with a maximum duty cycle of about 85%. The unit is operating in closed loop operation with (top) Flux maximization and (bottom) CRI maximization.
**Fig. 18:** Color errors measured at an array of setpoints spanning the accessible color triangle. The color error was less than 0.003 at all points.
Fig. 19: Long-term performance of a Phase 1 WRGB lamp. (Top) Evolution of the color error with time. After 12000 hours, the color error is still below 0.003 for all four setpoints. (Bottom) Change of actual color coordinates with time, with respect to the target.
Fig. 20: Performance of RGBW source with daylighting compensation enabled and an incandescent source of background light. The top graph shows the total flux and the LED-SIM flux as the incandescent lamp flux is increased. The middle graph shows the change in total color temperature as the incandescent flux is increased. The bottom graph shows the evolution of the combined spectrum.
Fig. 21: Variation of color coordinates, x (top left) and y (top right), intensity (lower left) and color error (lower right) for a Phase 3 reflector, with diffuser. The FWHM of the light distribution is 53 degrees. The color error is below 0.002 within the beam.
Fig. 22: Calculated LED junction temperatures, from thermal modeling. The calculation was done with different orientations of the Phase 3 unit. Only conduction and convection were included in the calculation. A simplified calculation for thermal radiation indicated that the junction temperatures would all be 10-15 degrees lower than those shown in the table. Taking radiation into account, all LED junction temperatures are below those required for 50,000 hour lifetime.
Fig. 23: Graphical User interface for control of LED-SIMs.
Fig. 24: Configuration Panel (top) and Commissioning Panel (bottom) in the user interface.
Fig. 25: EMI measurements, Common mode. The unit passed FCC-A, and nearly passed FCC-B.
Fig. 26: EMI measurements, Differential mode. The unit passed both FCC-A and FCC-B.
Fig. 27: LEXEL DLM. The product (top) consists of two boxes: 1) the light generation module, which includes the LEDs, primary optics, sensing and DC-DC electronics and 2) the AC-DC power supply. (Bottom) A mock up of a downlight luminaire using the LEXEL DLM product