HIGH EFFICIENCY INTEGRATED PACKAGE

Final Report

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EXECUTIVE SUMMARY

Solid-state lighting based on LEDs has emerged as a superior alternative to inefficient conventional lighting, particularly incandescent. LED lighting can lead to 80 percent energy savings; can last 50,000 hours – 2-50 times longer than most bulbs; and contains no toxic lead or mercury. However, to enable mass adoption, particularly at the consumer level, the cost of LED luminaires must be reduced by an order of magnitude while achieving superior efficiency, light quality and lifetime.

To become viable, energy-efficient replacement solutions must deliver system efficacies of ≥ 100 lumens per watt (LPW) with excellent color rendering (CRI > 85) at a cost that enables payback cycles of two years or less for commercial applications. This development will enable significant site energy savings as it targets commercial and retail lighting applications that are most sensitive to the lifetime operating costs with their extended operating hours per day. If costs are reduced substantially, dramatic energy savings can be realized by replacing incandescent lighting in the residential market as well.

In light of these challenges, Cree proposed to develop a multi-chip integrated LED package with an output of > 1000 lumens of warm white light operating at an efficacy of at least 128 LPW with a CRI > 85. This product will serve as the light engine for replacement lamps and luminaires. At the end of the proposed program, this integrated package was to be used in a proof-of-concept lamp prototype to demonstrate the component's viability in a common form factor.

During this project Cree SBTC developed an efficient, compact warm-white LED package with an integrated remote color down-converter. Via a combination of intensive optical, electrical, and thermal optimization, a package design was obtained that met nearly all project goals. This package emitted 1295 lm under instant-on, room-temperature testing conditions, with an efficacy of 128.4 lm/W at a color temperature of ~2873K and 83 CRI. As such, the package's performance exceeds DOE's warm-white phosphor LED efficacy target for 2013. At the end of the program, we assembled an A19 sized demonstration bulb housing the integrated package which met Energy Star intensity variation requirements. With further development to reduce overall component cost, we anticipate that an integrated remote converter package such as developed during this program will find application in compact, high-efficacy LED-based lamps, particularly those requiring omnidirectional emission.

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PROJECT OBJECTIVES

Cree's primary project objective was the development of a warm white light-emitting diode (LED) package with integrated remote down-converter that provided >1000 lumens at a color temperature of 3000 K, efficacy of at least 128 lumens per watt (LPW) and a color rendering index (CRI) of at least 85. This novel LED light source was designed for insertion into replacement lamps and novel luminaires for commercial and residential lighting applications. By the end of the program, Cree aimed to establish a production-capable, efficient, warm white LED package design that would be suitable for integration into replacement lamps and luminaires. As a proof-of-concept demonstrator, at the project's conclusion an A-lamp prototype meeting Energy Star specifications was to be fabricated.

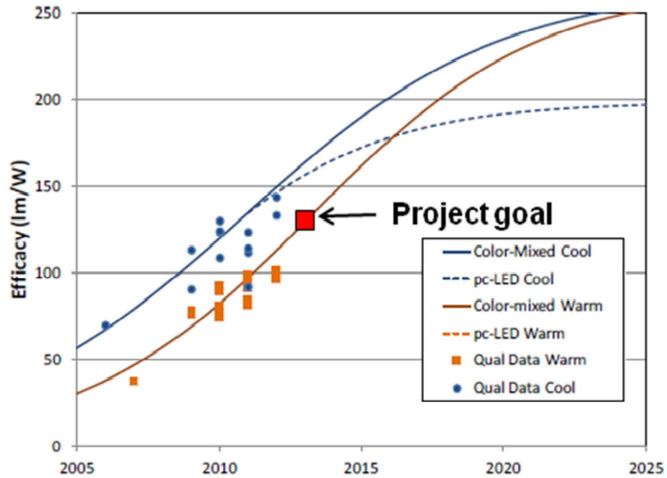

Fig. 1. This project's efficacy goal relative to performance projection for commercial warm-white LED packages (reproduced from DOE's Solid State Lighting R&D MYPP, April 2012.)

PROBLEM BACKGROUND

Solid-state lighting based on LEDs has emerged as a superior alternative to inefficient conventional lighting, particularly incandescent. LED lighting can lead to 80 percent energy savings; can last 50,000 hours – 2-50 times longer than most bulbs; and contains no toxic lead or mercury. However, to enable mass adoption, particularly at the consumer level, the cost of LED luminaires must be reduced by an order of magnitude while achieving superior efficiency, light quality and lifetime.

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In light of these challenges, Cree proposed to develop a multi-chip integrated LED package with an output of > 1000 lumens of warm white light operating at an efficacy of at least 128 LPW with a CRI > 85. This product will serve as the light engine for replacement lamps and luminaires. At the end of the proposed program, this integrated package was used in proof-of-concept lamp prototype to demonstrate the component's viability in a common form factor.

TECHNICAL APPROACH

This product development program built on Cree's high-brightness LED chip and package platforms to design a novel LED package that produces >1000 lm of warm white light at an efficacy of at least 128 LPW, and with a form factor suitable for integration into replacement lamps. A key feature of the proposed package design was the use of a remote down-converter element as a means to improve efficacy compared to conventional converter-on-chip designs. Potential advantages of a remote converter configuration over the conventional converter-on-chip approach include:

- Thermal isolation of the down-converter from the chip leads to less temperature quenching of the phosphor emission and long-term color stability;
- Improved conversion efficiency;
- Blue LEDs can be driven harder (*i.e.* higher lumens/$);
- System-level color binning (possibility for reduced binning cost);
- Intra-package light diffusion, simplifying optical design of omnidirectional lamps.

To meet project goals, Cree used a comprehensive approach to address the various integration trade-offs in the package design and fabrication. Specific areas of technology development included optimizing the package design for efficacy, thermal performance, color uniformity and long-term stability.

Work Plan

Task 1. Project Management: The progress of the program will be continuously monitored against the Project Management Plan (PMP).

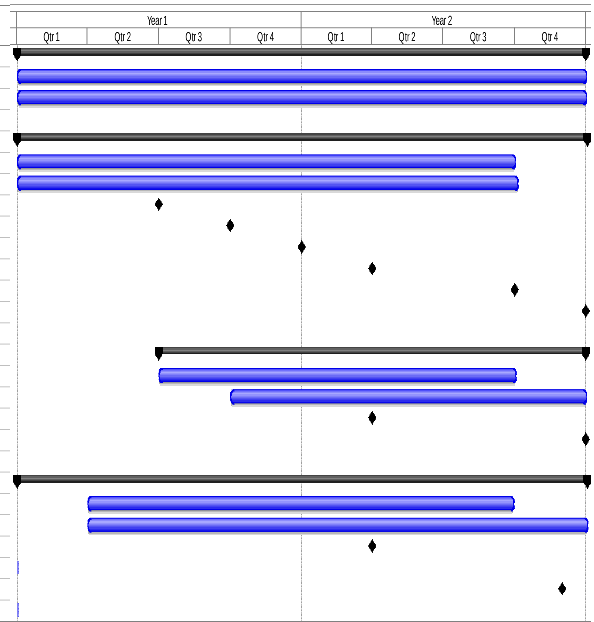
Task 2. Package Design and Fabrication: Cree will develop a 1000lm LED package and fabrication processes that addresses the associated thermal and optical trade-offs of the proposed remote converter approach. The integration of the LED chip and the down-converting media shall be designed to maintain high efficacy and color stability. All processes will be developed with manufacturability in mind to provide a low-cost, high-performance integrated package.

Task 3. Package Reliability: Cree will conduct studies to investigate the reliability of the new LED package design by testing the materials and fabrication processes used in the package to ensure they perform under accelerated testing conditions. Failure analysis will be performed to gain feedback for improving the package design and fabrication steps performed in Task 2.

Task 4. Package Integration into Luminaire: Cree will integrate the LED package developed under Task 2 into an omni-directional luminaire assembly. If necessary, a specifically tailored secondary optic will be designed to guide the light from the LED package into the specified output beam profile with minimal light loss.

Work Schedule

Task Name
1. Program Management
1.1 Monitor program progress, DOE reviews
1.2 Monthly and final reports
2. Package Design and Fabrication
2.1 Phosphor Integration with LEDs
2.2 Optical Cavity Design and Fabrication
Trade-off analysis of the phosphor placement completed
Component geometry (including optical cavity) and chip layout defined
Component demonstration with a remote converter providing 100 LPW at 3000K CCT
White reflectivity coating for optical cavity with reflectivity 95% or higher
White LED component with flux thermal efficiency of 86% (instant on to steady state)
White LED component providing 1000 lumens / 128 LPW at 3000K CCT and a CRI of 90
3. Component Reliability
3.1 High Temperature, High Humidity Reliability Testing
3.2 Failure Analysis
500 hour reliability with >90% lumen maint, color point shift within a 5-step MacAdam ellipse
1000 hour reliability with >90% lumen maint, color point shift within a 3-step MacAdam ellipse
4. Package Integration in Replacement Lamps
4.1 Secondary Optics Design and Fabrication for Omni-directional Beam Profile
4.2 Integration with LED Component
Diffusing optics with 90% optical efficiency and beam profile with an even luminous intensity with the 0-135 degree zone
Diffusing optics with 95% optical efficiency with A-lamp beam profiles as specified in Energy Star Program for Integral LED Lamps



TECHNICAL PROGRESS

Task 2 – Package Design and Fabrication

In Year 1, Cree designed and demonstrated a compact package prototype with a remote converter element design with a 1.25-inch diameter footprint (Fig. 2), which produced 950 lm at ~100 LPW (instant on, room temperature). This prototype had all the key package elements but the final package configuration still needed to be developed. As shown in the photo, the remote converter design was 3-dimensional. Less apparent elements of the prototype design included:

- Nine blue LED primary sources co-mounted on a planar, high thermal conductivity substrate for efficient heat flow and ease of luminaire assembly;
- Remote converter element comprising a phosphor coating applied to a relatively high thermal conductivity glass "substrate" using a novel, manufacturable (lab scale proof-of-concept) coating process for non-planar substrates;
- Highly engineered phosphor coating properties (e.g. materials, thickness) for heat dissipation, color mixing, and far-field intensity distribution;
- Low optical loss optical cavity for efficient recycling of inward-directed photons;

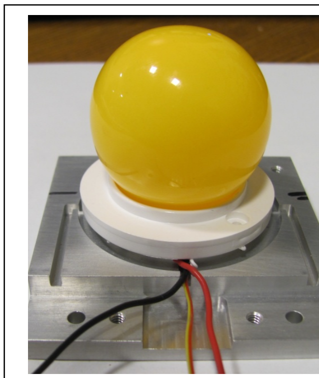
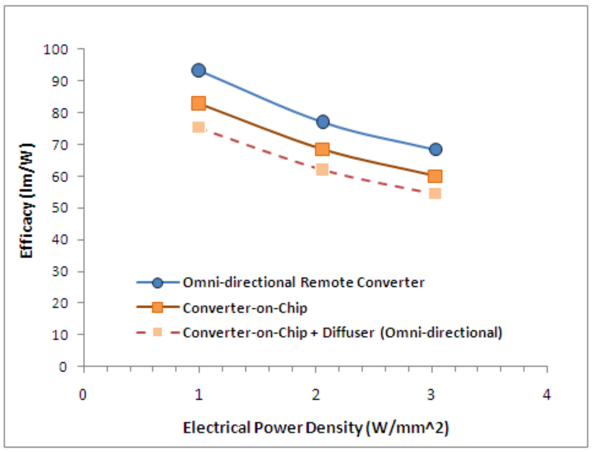


Fig. 2. Year 1 prototype ~1000 lm LED package with integrated remote converter. The prototype was mounted on a metal test fixture.

Efficacy

Compared to a conventional converter-on-chip solution under realistic operating conditions, the Year 1 novel remote converter package was 12-14% more efficient *when comparing the exact same blue LED chips* as the primary light source (see Fig. 3). Moreover, this gain understates the advantage of the remote configuration for the intended applications since the converter-on-chip solution is a directional emitter. Adding a diffuser to the latter in order to make the output omni-directional reduces its flux. Thus, on a like-to-like basis the Year 1 prototype remote converter package was ~20% more efficient.

In absolute terms the remote converter package output at the end of Year 1 was 994 lm with an efficacy of 110 LPW when operating at 35 A/cm^2 and an LED junction temperature of ~85°C. Color temperature of the white emission was 3015K, and the CRI was 81. At room temperature, the instant-on output was 1109lm with an efficacy of 116 LPW, which met and exceeded a key Year 1 milestone.



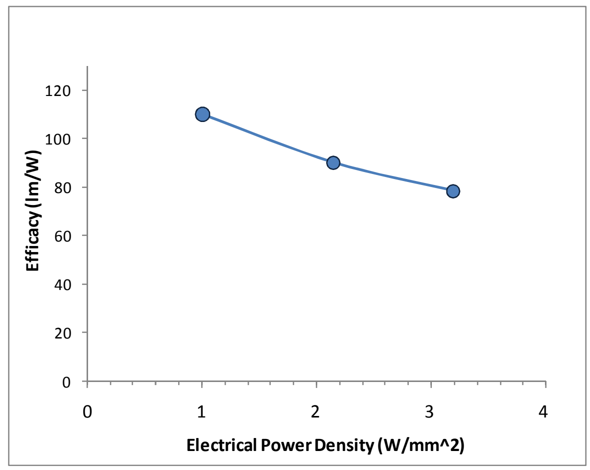


Fig. 3. Relative optical performance of the remote converter prototype and conventional converter-on-chip LEDs (left). The lowest power density shown corresponds to an LED junction temperature of 85°C and operating current density of 35 A/cm^2. Year 1 remote converter prototype performance under the same conditions was 110 LPW (right). All data were measured using a NIST-calibrated integrating sphere.

In Year 2, in an effort to improve prototype package efficacy while minimizing overall package size and maximizing emission omni-directionality, we evaluated several package design iterations by varying package substrate size and type, blue chip size and layout, and remote converter composition and geometry. We tested each assembled configuration by measuring total lumen output as well as white lumens emitted per watt of blue emission (a measure of remote converter efficiency). Results for several designs are shown in Fig. 4, in which it is evident that Design 4 had superior luminous flux at a desired color point.

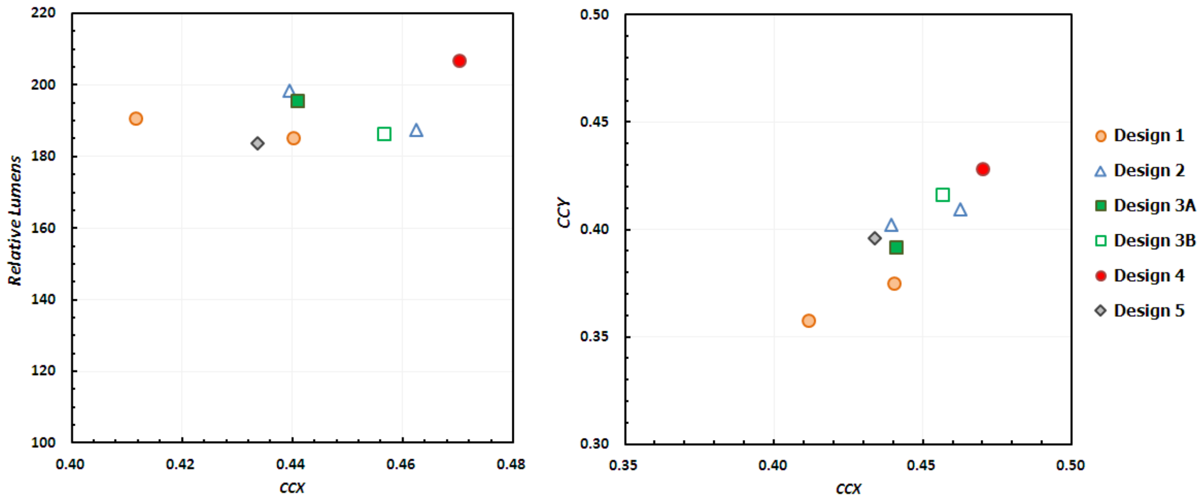


Fig. 4. Left: lumens emitted by various prototype package designs vs. color point ccx. Right: comparison of the color points (ccx, ccy) of the various designs.

As shown in Fig. 5, the final prototype package design consisted of an optimized layout of blue-emitting chips on a hybrid ceramic-metal substrate, over-coated with a reflective coating (see below) and capped by the remote converter element. This compact design was developed with an eye for use in compact omnidirectional lamps such as the A-19, which require relatively uniform emission vs. angle.

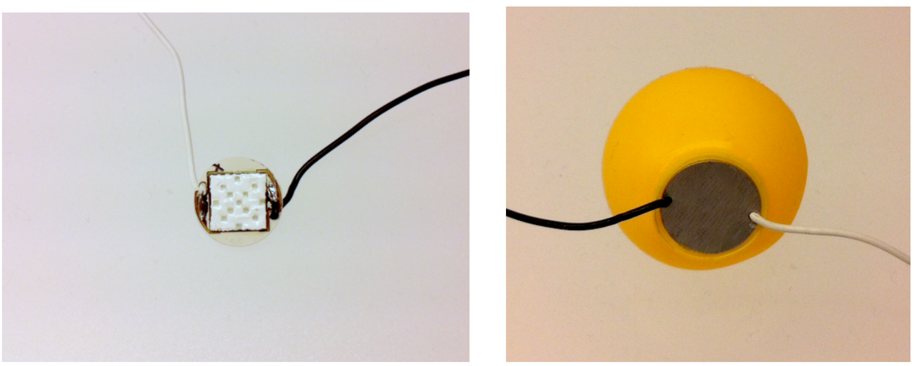


Fig. 5. Left: Blue-emitting chips on the package substrate prior to full coverage with a highly reflective coating. Right: Bottom view of fully assembled package, indicating integral fit of remote converter on package substrate.

The final prototype package configuration was tested in a calibrated integrating sphere to quantify its performance. As shown in Fig. 6, it was found to meet or exceed all project goals with the exception of CRI, which was 83 vs. the project goal of 85. However, the correlated color temperature (CCT) of 2873K was lower than the project goal of 3000K. Therefore if another package fabrication iteration were undertaken to adjust CCT to 3000K and CRI to 85, the net efficacy of ~128 LPW would remain approximately the same.

Characteristic	Value
Current Density per chip	35.0 A/cm^2
Forward Voltage	39.88 V
Input Power Density	1.07 W/mm^2
Radiant Flux	3.95 W
Luminous Flux	**1295.3 lm**
CIE u′, v′	0.2530, 0.5341
CCT	**2873 K**
CRI	83
Wall-plug Efficiency	39.2 %
Efficacy	**128.4 lm/W**

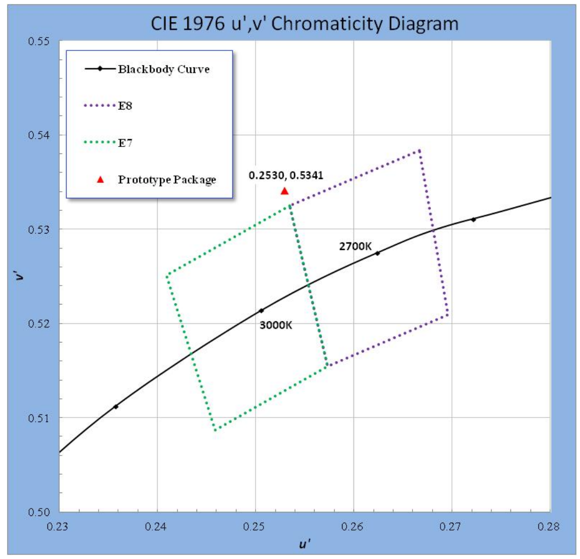


Fig. 6. Left: "Instant on" photometric characteristics of the prototype package measured at room temperature and a current density of 35 A/cm^2. Right: Color point of prototype package relative to the blackbody locus.

Thermal Efficiency

An important consideration for the remote converter package design is ensuring that the phosphor particles do not overheat while making the package fit in a compact footprint. For a large remote converter geometry, the flux density incident on the converter material is low and phosphor heating is not an issue. However, large geometries are impractical for cost and size reasons. On the other hand, phosphor heating is a challenge in a compact remote geometry, where the incident flux density remains moderately high but a short direct path for heat flow (*e.g.* through the LED chip) is absent, unless care is taken in its design.

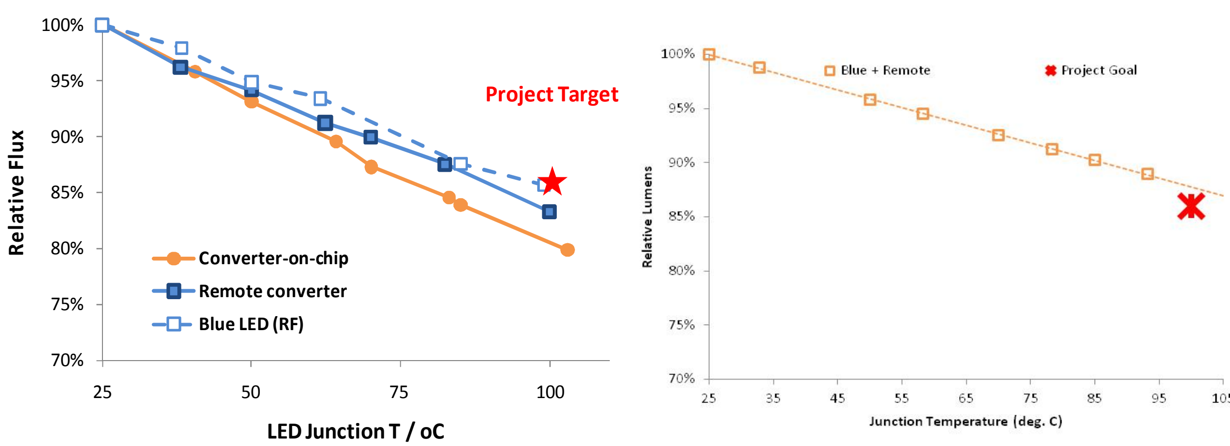


Fig. 7. Left: Flux thermal efficiency of the prototype package at the end of Year 1. Right: Year 2 (final prototype) flux thermal efficiency, which exceeded the project goal.

A useful package metric is the so-called flux thermal efficiency: the percent of the instant-on, room temperature, luminous flux maintained under steady state, high-temperature operating conditions. The first-generation remote converter package design exhibited a thermal efficiency that was ~4% better than a comparable converter-on-chip LED package due to the remote phosphor particles staying cooler. Despite a reduction in the size of the package during Year 2, which could potentially impact the thermal efficiency, the final prototype package was found to have a flux thermal efficiency of ~88% at 100°C (see Fig. 7), which exceeded the project goal of 86%.

Color and Luminous Intensity Distribution

Other key attributes of the remote converter package design were the intensity and color emission characteristics vs. viewing angle. Bearing in mind the intended application, the prototype package design and fabrication processes went through a large number of iterations during the first and second year in an effort to achieve as omni-directional white light emission as possible without the need for secondary optics.

Energy Star requirements for omni-directional replacement lamps require an even distribution (within 20% of the mean) of luminous intensity within the 0° to 135° zone, along with vertical symmetry. The earlier prototype LED package designs approached but did not meet these stringent requirements as is (*i.e.* without additional optics). In Year 1 we were able to achieve an even intensity distribution over approximately 0° to 115° but the intensity fell off faster than desired at higher angles. The shortfall was addressed in Year 2 using refinements to the remote converter design (particularly its shape) in combination with moderate diffusion in the demonstration A-bulb envelope.

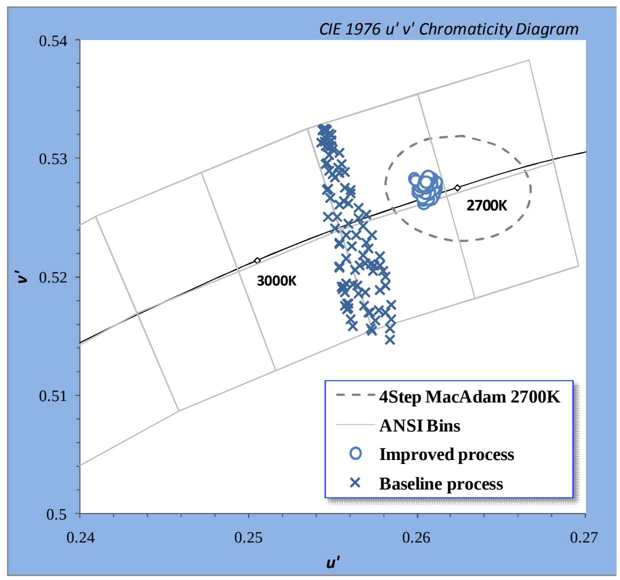


Fig. 8. Year 1 prototype LED package far-field color point uniformity over a range of 0° - 150° (zero is the vertical optical axis) and at 8 different azimuths. The data were measured using a gonio-spectrophotometer.

Color uniformity was particularly poor in early design iterations, indicative of the underlying challenge of mixing blue light from directional (quasi-Lambertian) LEDs with yellow down-converted light from the more or less omni-directional remote converter element. Through a combination of optical modeling and experimental trial and error we were able to solve the color mixing problem, such that the light output from later design iterations was uniform in color to within two standard color matching steps over the full range of viewing angles (see Fig. 8). Critically, we were able to achieve this with only a small (< 2%) hit to the package efficacy.

High-Reflectivity Coating

Another area of progress was the development of a thin, patternable, thermally stable, high reflectivity (total R > 95%) coating that could be applied to the internal surfaces of the remote converter prototype package. Since approximately half of the down-converted light from a remote converter element is scattered inwards it is very important for any surfaces this light interacts with to have low absorption losses – otherwise the efficacy advantages of the remote converter can be easily lost. Commercial and Cree proprietary high reflectivity materials existed at the start of the project. However, these were not suitable for the compact remote converter packages being developed here for a number of reasons, including a limited temperature range (not able to stand chip reflow), or too thick (needed to reach the target *R* value), or not able to be patterned (and leave uncoated space for the LED chips) in a practical way. Building on earlier work on blanket coatings, during this project we developed a novel, scalable, patterned coating process that resulted in up to 6% flux improvement, depending on the optical cavity and LED details. Moreover, the coating maintained a total reflectivity of 95% even after being briefly subjected to a temperature of ~290°C (such as experienced during a solder reflow).

Optical Coating	Reflectivity (%)	
	Before AuSn Package Reflow	After AuSn Package Reflow
Commercial Coating	85%	66%
Custom Coating	96%	95%

Total (specular + diffuse) reflectivity, *R*, of the coating used in the prototype package. Reflectivity was measured on coupons using a diffuse/specular reflectometer setup and compared to known standards.

Task 3 – Package Reliability

Long lifetime under realistic operating conditions is of critical importance for a viable commercial LED product. Initially, the focus was on testing the new materials and fabrication processes being developed for the remote converter element of the package. Initial reliability testing of the remote converter at 85°C (ambient), a typical accelerated lifetime test for LED packages, showed a color shift of less than 0.001 Δu'v' after more than 3,000 hours of operation. Note that the test was not performed on a complete package format, since this was still being finalized at the time. However, we believe the test did stress the critical high risk portions of the new design. Satisfactory reliability results were also achieved for parts tested at 1.8 times the incident flux density necessary to reach an output of 1000 lumens, which suggest we have further room to reduce the prototype package dimensions in the future. Tests at even higher flux density are in progress.

The final prototype package was run through Cree's standard accelerated lifetime testing, and readily passed acceptance criteria for luminous flux and color point stability (see Fig. 9). These results indicate the utility of this package design in lamp applications where the heat load on the package is relatively high due to space and/or heat sink design constraints.

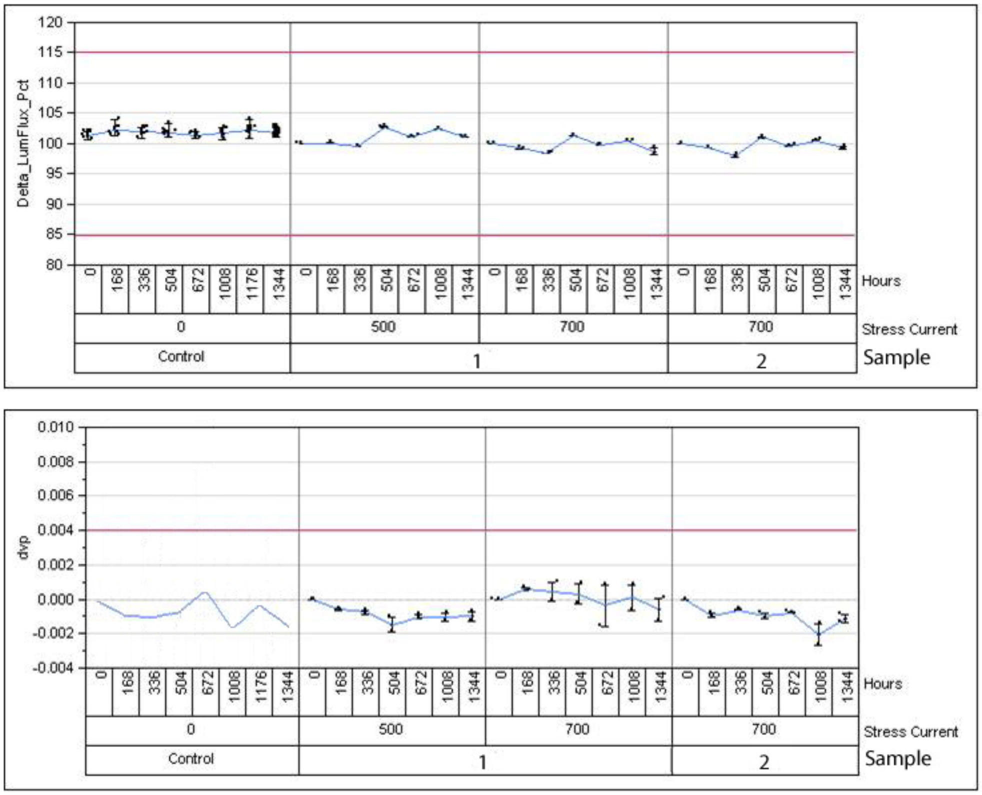


Fig. 9. Top: Luminous flux variation of the final prototype package design during high-temperature accelerated testing. Bottom: color point variation during this testing. Both characteristics remained well within our acceptance criteria.

Highly Accelerated Testing of Remote Converter Binder Materials

While package reliability testing was of chief importance for validation, we also developed new methods of hyper-accelerated reliability testing for the remote converter binder materials by themselves. One of the test platforms we believe has the best potential to serve as an accurate predictor of silicone reliability in long-duration LED testing is a compact oven in which silicone is simultaneously heated (~200°C) and exposed to blue light flux from an external source. The sample's transmittance of blue light was periodically measured to quantify the degree of yellowing when exposed to these conditions. As a baseline we tested two standard, well characterized silicones for up to 10 days at 200°C with and without blue light flux. In Fig. 10 it is evident that both silicones exhibited a much faster rate of yellowing when exposed to both heat and light, and with a bi-modal rate which suggests two different degradation mechanisms may have been responsible. This is analogous to behavior which has been observed during standard long-duration (>3,000 hr.) LED reliability testing, and is a correlation that preliminarily validates this new technique.

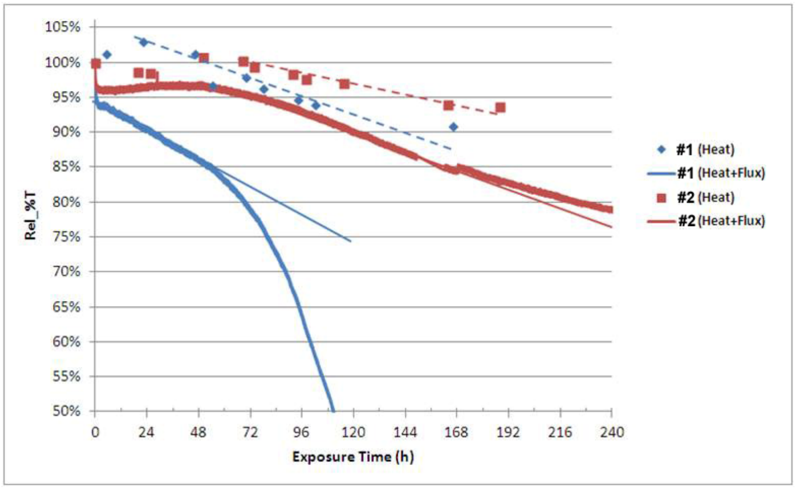


Fig. 10. Relative change in transmittance at 450nm of two standard silicone samples during exposure to heat with and without blue light flux. The yellowing rates were accelerated in the presence of blue light flux, particularly for silicone #1.

Narrow-line converters

In the effort to increase remote converter efficacy we investigated alternatives to conventional red-emitting phosphors. While it is possible to achieve very high CRI warm white spectra using an appropriate blend of conventional phosphors, doing so results in reduced efficacy. In an effort to minimize this effect, we considered alternative materials that provide narrower red emission (full width at half maximum of < 40nm), since they offer white spectral power distributions with a superior luminous efficacy of radiation (LER). Narrow-line converters (NLCs) have desirably narrow emission characteristics but, compared to conventional red phosphors, have generally suffered from extremely poor reliability. However, down-converters in a remote converter geometry are subject to considerably less heat and optical flux density than when they are located directly on chip. Thus we investigated their use in this configuration.

To validate the study of NLCs, Cree developed a sophisticated spreadsheet-based spectral modeling tool that has the ability to evaluate and compare the anticipated efficacy, CCT, and CRI of white LEDs fabricated from different combinations of emitters and down-converters. The principal motivation behind this work was the “apples to apples” objective comparison of new down-converter formulations or approaches (*e.g.* new phosphor blends, NLCs). We also wanted to be able to compare potential all-down-converter solutions to Cree’s existing high-performance TrueWhite® approach for warm white luminaires, which utilizes red-emitting chips in combination with blue chips coated with yellow/green phosphors.

The color-mixing model was validated by comparing calculated and measured efficacy vs. power density of various all-phosphor and TrueWhite® configurations. We then applied the model to the use of NLCs for several CRI, and CCT combinations. An example is shown in Fig. 11, in which the efficacy vs. input power density of NLCs are compared to conventional phosphors and TrueWhite® (in three configurations), at 80 CRI and a temperature of 25°C. It is predicted that white LEDs using NLCs have comparable efficacy to the best TrueWhite approaches at room temperature, and may have superior efficacy at elevated temperature.

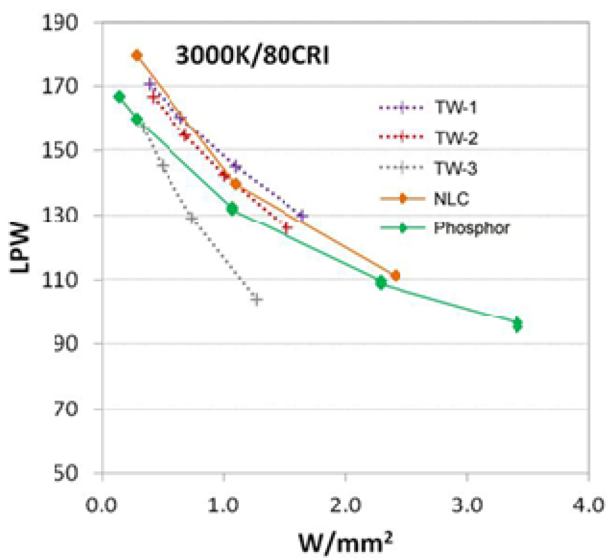


Fig. 11. Calculated 25°C efficacy vs. input power density for 80 CRI white LEDs based on narrow-line converters compared to conventional phosphors and TrueWhite® (in three configurations).

We have worked with a supplier of red-emitting NLCs to evaluate their robustness under representative LED conditions. As shown in Fig. 12, we typically found there was an initial rise in luminous flux upon exposure to blue light, the origin of which was unclear. Then, depending on the amount of blue light power and temperature, the luminous flux of the NLCs decreased over time. This was found to be accelerated by higher blue light flux levels, suggested a photo-catalyzed degradation mechanism. Although improvements were made during the project, such degradation requires significant further improvement before we can consider incorporating NLCs in any type of down-converter application, including remote converter elements.

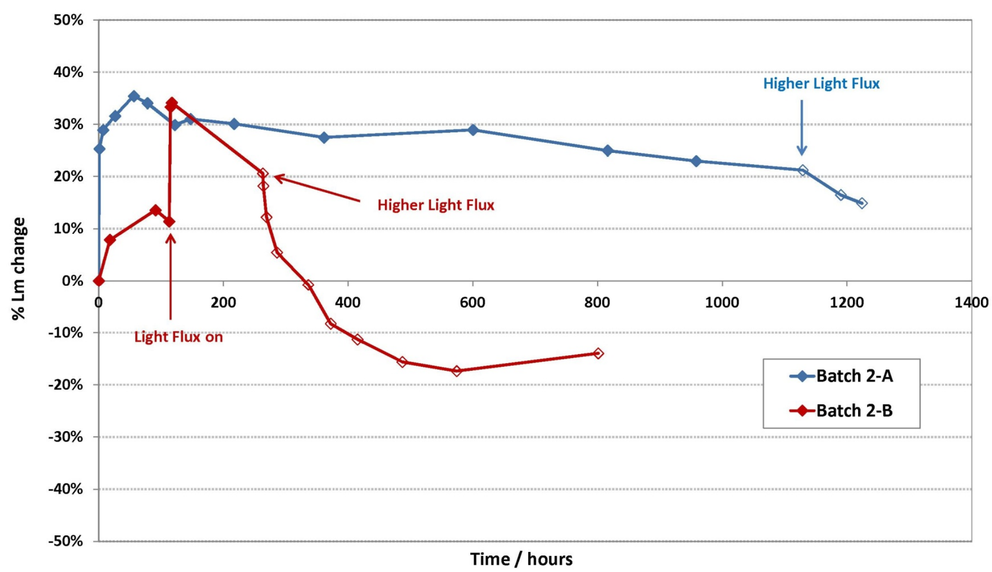


Fig. 12. Luminous flux change vs. time during accelerated testing of two NLC batches.

Task 4 – Package Integration into Replacement Lamp

During Year 1 we spent only a limited amount of effort on the design of the integrated A-lamp lamp into which the prototype package would be incorporated for the end-of-project deliverable. Such work was planned primarily for Year 2 once the basic high-lumen package design had been worked out. However, based on the promising efficacy results and preliminary reliability data for the prototype 1000 lm packages, we created a provisional 'product' datasheet and provided samples to a number of OEM manufacturers of replacement lamps with whom Cree already has a business relationship. For demonstration purposes we also provided mockups of the prototype package integrated into an A-lamp reference design (see Fig. 13), including a thermal solution and electrical driver. As shown in the photo, the reference design does not include any secondary optics, but it is a fully functional replacement lamp that may be suitable for some applications as is.

Fig. 13. Early A-lamp demonstration design using a remote converter prototype package as the light source.

Feedback from the OEM manufacturers included independent confirmation of optical performance, as well as positive comments on the overall size and omni-directional emission characteristics of the prototype LED package. In some cases concern was expressed regarding the off-state (orange-ish) color, which was not entirely unexpected. Universally, cost estimates appeared to be a critical concern for this implementation. As a result, reducing the potential cost of the package design became an area of the focus during Year 2.

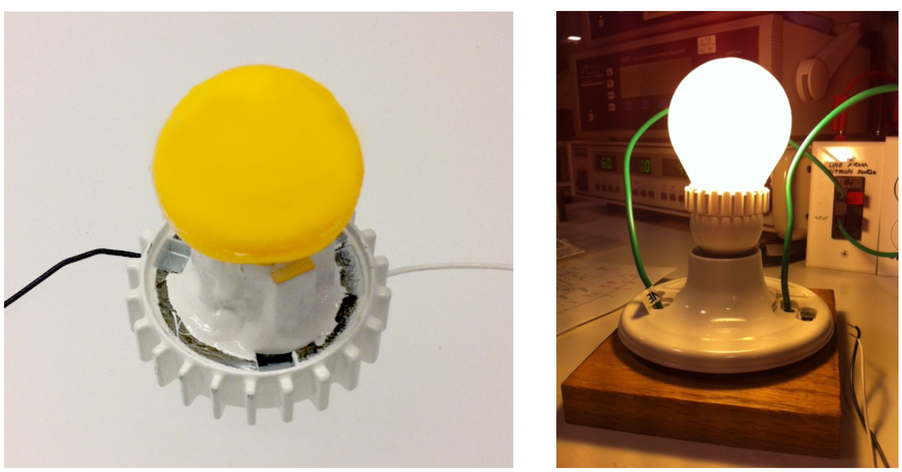


Fig. 14. Photographs of the prototype integrated remote converter LED package on a modified, coated Cree filament tower (left) and the fully assembled and illuminated A-bulb (right).

During the latter part of Year 2, we developed a demonstration A19 bulb design that was largely based on the components in Cree's recently released bulbs. We modified the filament tower to incorporate a modified heat sink upon which the prototype LED package could be placed (see Fig. 14). This redesign was largely intended to support and optimally position the package in the luminaire. The bulb was assembled to include a custom-modified electrical driver board which was derived from the commercial version. The bulb's emission intensity vs. angle was measured for three in-plane azimuths (rotation angles about the vertical axis) of 0°, 45°, and 90°. As shown in Fig. 15, the variation in emission intensity from average was ~19% between 0-135° from vertical for all cases, and ~13% of total emission lay between 135° and 180° from vertical. We therefore met the final project milestone of meeting Energy Star requirements in a realistic demonstration bulb.

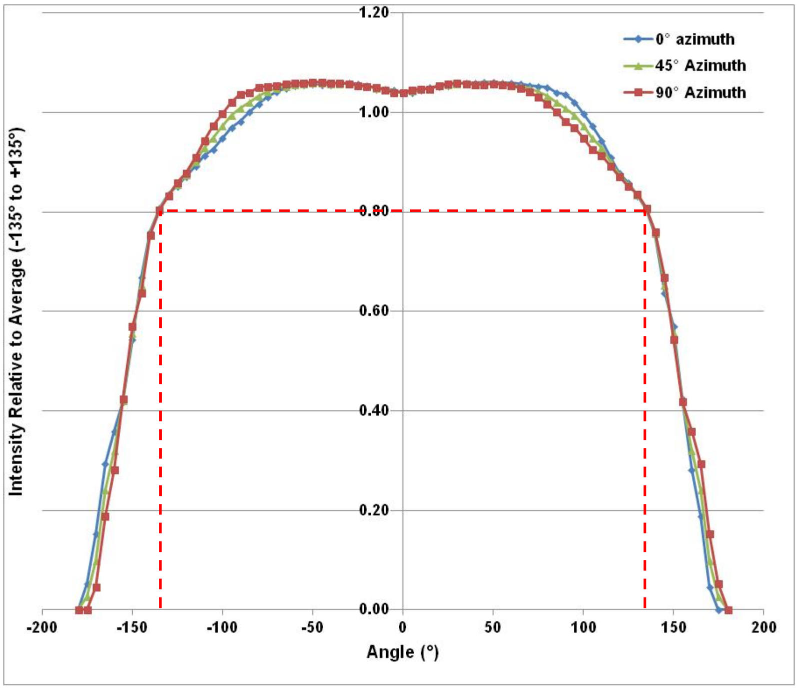


Fig. 15. Demonstration bulb intensity vs. emission angle from vertical relative to the average intensity between 0-135° from vertical. Red dotted lines indicate Energy Star requirements of < 20% variation from the mean intensity in the zone between 0 and 135° from normal.

Milestones / Deliverables

Budget Period 1

Title: Trade-off Analysis of the phosphor placement
Success Criteria: Selection of phosphor integration scheme in the package
Planned Date: February, 1st 2012
Verification Method: Selected phosphor integration scheme in the package will be documented in a report.
Status: This milestone was met, albeit somewhat later than originally planned. We originally considered the possibility of placing the phosphor coating on a heat sink surface within the optical cavity for thermal efficiency reasons. However, through modeling and experiments this was found to be unnecessary and less optically efficient than the more conventional placement on a transparent "substrate" as described above.

Title: Package geometry and chip layout defined
Success Criteria: Complete design of the LED package with its geometry defined in a document.
Planned Date: May, 1st 2012
Verification Method: Specification for the LED package will be documented in a report.

Status: This milestone was met on time, with the choice of a 3-dimensional remote converter element placed above a planar array of blue LEDs. High flux density reliability results and cost considerations mean that, going forward, we will look to shrink the package footprint while keeping the same basic layout.

Title: LED package prototype fabricated
Success Criteria: Prototype package provides 100 LPW at 3000 K CCT when measured.
Planned Date: August 1st 2012
Verification Method: White light emitting LED package will be fabricated and light emission vs. input electrical power will be measured using a calibrated integrating sphere measurement system.
Status: This milestone was met on time. Best to-date prototypes demonstrated 110 LPW at LED junction temperature of 85°C.

Budget Period 2

Title: White reflectivity coating
Success Criteria: White reflective coating provides a reflectivity of 95% or more.
Planned Date: November 1st 2012
Verification Method: Samples will be fabricated and the reflectivity will be verified on a UV-VIS spectrophotometer with a diffuse reflectivity accessory (essentially an integrating sphere mounted onto the spectrophotometer) calibrated against a standard sample with known reflectivity.
Status: This milestone was met by August 2012, ahead of schedule.

Title: LED package with 500 hours accelerated testing.
Success Criteria: Measure > 90% lumen maintenance and color point shift (u' and v') within a 5-step MacAdam ellipse after 500 hours of reliability testing
Planned Date: November 1st 2012
Verification Method: Samples will be fabricated and output verified using a calibrated integrating sphere measurement system at intervals of 168 hours until 504 hours reliability testing has been completed.
Status: Accelerated testing on the high-risk portion of the Year 1 package design met this target ahead of time. Later testing on the final prototype package geometry also met this target, despite its different geometry.

Title: Secondary optics prototype fabricated
Success Criteria: A secondary optics measuring 90% optical efficiency and beam profile with an even luminous intensity within the 0-135^{o} zone.
Planned Date: November 1st 2012
Verification Method: The efficiency verified using a calibrated integrating sphere measurement system and the beam profile using a calibrated gonio-photometer.
Status: Met ahead of time.

Title: White LED package with improved flux thermal efficiency
Success Criteria: Prototype package maintains 86% of its flux at a junction temperature of 100^{o}C compared to the total flux instant-on (Tj=25^{o}C).

Planned Date: May 1st 2013
Verification Method: White light emitting LED package will be fabricated and light emission vs. input electrical power will be measured using a calibrated integrating sphere measurement system, first at instant-on (25°C) and then at a current sufficient to raise the junction temperature to 100°C.
Status: Met on time, and target was exceeded by a few percent.

Title: Final White LED package prototype fabricated
Success Criteria: Prototype package providing 1000 lumens and 128 LPW at 3000 K CCT and CRI > 85 when measured.
Planned Date: August 1st 2013
Verification Method: White light emitting LED package will be fabricated and light emission vs. input electrical power will be measured using a calibrated integrating sphere measurement system.
Status: Milestone goals were met, with the exception that CRI (83) was slightly lower than the target of 85.

Title: LED package with 1,000 hours accelerated testing
Success Criteria: Measure > 90% lumen maintenance and color point shift (u' and v') within a 3-step MacAdam ellipse after 1000 hours of reliability testing
Planned Date: August 1st 2013
Verification Method: Samples will be fabricated and output verified using a calibrated integrating sphere measurement system at intervals of 168 hours until 1008 hours reliability testing has been completed.
Status: Milestone met on time.

Title: Final secondary optics prototype demonstration
Success Criteria: A prototype diffusing optics measuring 95% optical efficiency and A-lamp beam profile with an even luminous intensity within the 0-135° zone and at least 5% of the total flux emitted in the 135-180° zone using the integrated package developed in Task 2.
Planned Date: August 1st 2013
Verification Method: The efficiency verified using a calibrated integrating sphere measurement system and the beam profile using a calibrated gonio-photometer.
Status: Final demonstration lamp fabrication and testing delayed by ~1 month due to supplier delays, but otherwise accomplished in line with project goals.

CONCLUSIONS

During this two-year project Cree SBTC developed an efficient, compact warm white LED package with an integrated remote color down-converter. Via a combination of intensive optical, electrical, and thermal optimization, a package design was obtained that met nearly all project goals, and exceeds DOE's projected warm-white phosphor-converted efficacy target for 2013. With further optimization to reduce overall component cost, we anticipate that such a remote converter package will find application in compact, high-efficacy LED-based lamps, particularly those requiring quasi-omnidirectional emission.