High Quality Down Lighting Luminaire with 73% Overall System Efficiency

Final Report

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EXECUTIVE SUMMARY

This report summarizes work to develop a high flux, high efficiency LED-based downlight at OSRAM SYLVANIA under US Department of Energy contract DE-FC26-08NT01582. A new high power LED and electronic driver were developed for these downlights. The LED achieved 100 lumens per watt efficacy and 1700 lumen flux output at a correlated color temperature of 3500K. The driver had 90% electrical conversion efficiency while maintaining excellent power quality with power factor >0.99, and total harmonic distortion <10%. Two styles of downlights using the LED and driver were shown to exceed the project targets for steady-state luminous efficacy and flux of 70 lumens per watt and 1300 lumens, respectively. Compared to similar existing downlights using compact fluorescent or LED sources, these downlights had much higher efficacy at nearly the same luminous flux.

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PROJECT OBJECTIVE

The objective of this work was to demonstrate a LED downlight with (1) luminous efficacy of 70 lumens per watt, (2) luminous flux of 1300 lumens, (3) good color quality, and (4) driver with good power quality.

(1) 70LPW steady-state luminaire efficacy. To reach this level of performance, a combination of ~100LPW LED source and luminaire efficiency of 73% was proposed. The luminaire efficiency includes electrical, thermal, and optical losses.

(2) Luminous flux of 1300 lumens. Since 70LPW from the luminaire is targeted, this requirement translates to an input power of ~18.6W.

(3) Good color quality. Defined as 3500K correlated color temperature (CCT) within ANSI specification and a color rendering index (Ra) of ≥80.

(4) Driver with good power quality. In addition to having ~90% efficiency with no visible flicker, have a power factor (PF) >0.90 and low total harmonic distortion (THD).

At the time of the proposal, the 73% luminaire efficiency was the DOE MYPP goal for year 2015[1]:

	DOE 2006	DOE 2010	DOE 2012	DOE 2015	OSI 2010
Thermal Efficiency	80%	84%	87%	90%	95%
Driver Efficiency	85%	87%	88%	90%	90%
Fixture Efficiency	75%	82%	85%	90%	85%
Resultant Luminaire Efficiency	51%	60%	65%	73%	73%

This work proposed to meet 73% luminaire efficiency by 2010, five years before the roadmap projection.

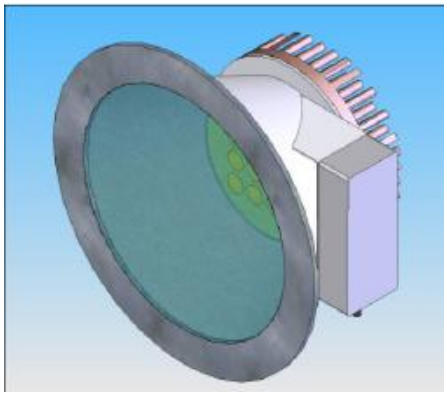


Figure 1. Initial rendering of proposed luminaire.

TECHNICAL APPROACH

LED SOURCE

The performance goals for the LED source follow directly from the luminaire targets. Since the luminaire efficacy 70LPW and resultant luminaire efficiency of 73% is expected, the LED must have an efficacy of 70/0.73 = 96LPW. To achieve the luminaire luminous flux of 1300 lumens with an expected driver efficiency of 90%, the power delivered to the LED should be 1300/70*0.90 = 16.7 watts. So the LED source must be capable of 96LPW efficacy with 16.7W input before electrical, optical, and thermal losses are considered. In addition, the LED CCT should be 3500K with Ra ≥ 80 to ensure good color quality.

The LED consisted of the following components:

(1) Metal core printed circuit board substrate. Consisted of an aluminum base plate, dielectric layer, copper circuit traces with gold metallization, and white solder mask.

(2) Reflective circuit board coating. Proprietary composition having high reflectivity to increase light extraction of phosphor-scattered light.

(3) Blue LED chips. Largely hexagonal array of 19 1mm^2 blue LED chips. Supplied by OSRAM Opto Semiconductors.

(4) Clear silicone encapsulation. Protects LED chips and wire bonds. Also maximizes light extraction from LED chips.

(5) Silicone-encapsulated phosphor. Blend of phosphor powders in clear silicone for conversion of blue LED light to correct chromaticity.

(6) Glass or ceramic phosphor substrate. Laterally spreads phosphor-generated heat while providing protection to underlying LED chips and wire bonds.

(7) Connector and zener diode. Provides detachable electrical connection and protection from electrostatic discharges.

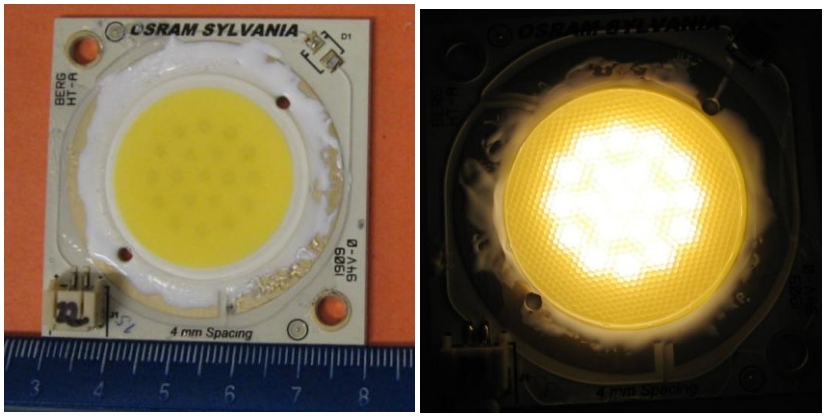


Figure 2. Photographs of LED components. Off-state with glass phosphor substrate (left) and lit with textured ceramic substrate (right).

The LED was initially tested at 25°C using pulsed current measurements at 1% duty cycle. Results at different drive currents are shown in Table 1.

Table 1. LED performance at 25°C.

Drive current (mA)	Efficacy (lm/W)	Flux (lm)	CCT (K)	CRI
280	101	1702	3474	83
350	96	2061	3483	83
700	78	3540	3540	82
1000	69	4831	3611	82

At 280mA drive current, the LED exceeds project requirements for efficacy and flux by about 5 percent, meets the ANSI 3500K CCT chromaticity requirement, and satisfies the CRI requirement. This drive current was supplied from the driver in the completed luminaires.

ELECTRONICS

One the challenges encountered when powering LEDs from AC mains-derived power supplies is producing light that is free of low frequency, visible ripple/flicker components. Power from an AC source is delivered in a pulsating fashion at twice the mains frequency, or 120Hz in North America. Such ripple components are observed with the older fluorescent lamps that utilized magnetic ballasts and are undesirable.

The trivial solution for reduction of visible ripple/flicker – the use of bulk storage capacitor - has a negative impact on the AC mains power factor (PF) and total harmonic distortion (THD), with conversion efficiency remaining essentially unchanged. For commercial applications, a power factor ≥0.9 is required for DOE Energy Star for solid-state luminaires operating with lamp power >5W[2]. More complex solutions that reduce or eliminate 120Hz LED ripple current while maintaining relatively high PF and low THD often result in lower electrical conversion efficiency than simpler designs. Due to the nearly fixed losses present in some power conversion designs, operating at lower power levels also presents a challenge in achieving high conversion efficiency. In addition, more complex systems are often less reliable and more costly than simpler ones. Thus, the design of the LED power supply involved a variety of tradeoffs that affect performance, cost and reliability.

The power supply topology utilized for this down light design is comprised of two stages – a boost power factor correction (PFC) stage followed by a switching constant current driver. While this approach does not produce the highest electrical conversion efficiency, it does ensure the power supply will meet power quality demands and supply the cleanest drive current for the LED load, allowing the best quality of light achievable by the light engine. The design was based on a commercially produced Sylvania product with a proven record for reliability.

Some of the factors that worked in favor of maximizing conversion efficiency are operation at a single AC mains voltage (120VRMS, nominal), operation into a fixed load and utilization of an integrated luminaire where the internal components are inaccessible to the consumer. The power electronics components and methods utilized in the design are fairly mature, helping keep cost low, reducing risk for sourcing components and capitalizing on proven reliability. For example, the boost PFC stage is commonly used in other electronics appliances, such as personal computers and TVs.

The components that make up the luminaire have associated efficiency losses that depend on operating point (e.g. drive current, voltage, power, temperature, frequency) amongst other factors. Quantifying the loss mechanisms in the component parts and understanding how these mechanisms are interrelated are necessary for optimizing the luminaire efficacy. The process undertaken in the electrical design involved coordination with the optical and thermal design for the luminaire.

In summary, we were able to achieve excellent performance for high quality LED drive current and power quality on the AC mains connection. Operating at an LED load power of approximately 18W the power factor is >0.99, total harmonic distortion < 10%, and electrical conversion efficiency ≥90%.

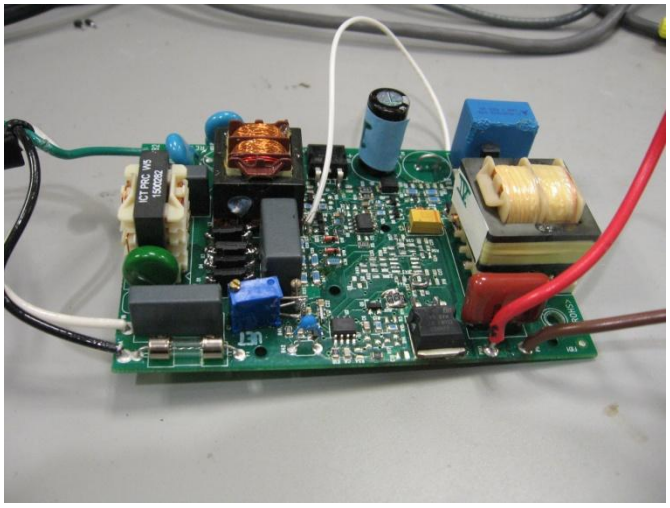


Figure 3. Photograph of a driver on a rectangular circuit board.

The driver for the downlight luminaire must deliver 18.6W to the LED string so that the luminaire can achieve the desired 1300lm steady state luminous flux. The primary goal to be reached 90% conversion efficiency from AC wall voltage input to the 18.6W DC output. Achieving high efficiency at such low power outputs is challenging because the unavoidable rectification and resistive losses make up a relatively large proportion of the power output.

Other targets include power factor of 0.9 and zero off-state power consumption. A complete list of driver specifications and results are found in Table 2.

Table 2. Driver targets and actual performance.

Specification	Target	Actual performance
Efficiency (P_{in}/P_{out})	90%	91%
Power factor	0.90	>0.99
Power output	18.6W	18.6W
Off-state power consumption	0	0
Total harmonic distortion	Not specified	<10%

THERMAL MANAGEMENT

Thermal management efforts were focused on two critical areas of the luminaire: (1) between the LED junctions and the base of the circuit board on which they are mounted and (2) between the phosphor and heat sink. Because the power level is under 20W and the luminaire housing is a sufficiently large, the housing to ambient thermal resistance was not a bottleneck.

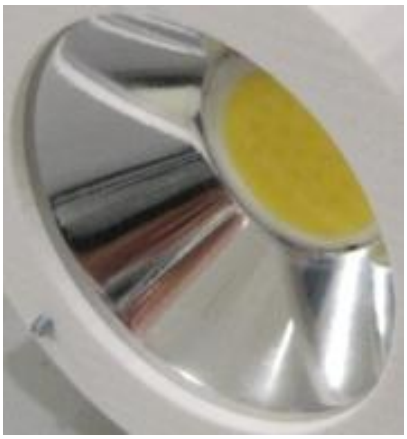
To address the thermal resistance between the LED junction and heat sink the following variables were studied through simulation and experiment: spacing between adjacent LED chips, copper circuit thickness and pad shape, aluminum base plate thickness, chip bonding epoxy material and application technique. The final result was a 6K/W thermal resistance between junction and bottom of aluminum base plate. This compares favorably to values typical for a commercial 1W class LED package soldered to a metal core printed circuit board.

The phosphor itself generates about 3W of heat during operation due to the Stokes shift and less than unity phosphor quantum efficiency. Because the phosphor is not in direct contact with the LED chip as in most commercial LED packages, the phosphor heat needs an alternative path to the heat sink. The 3W of phosphor heat is somewhat localized in regions of silicone above each of the 19 LED chips. Since silicone is a poor conductor of heat, a “phosphor substrate” of higher thermal conductivity was added in direct contact with the silicone phosphor layer. Two materials were used for phosphor substrates: optical glass and polycrystalline alumina ceramic, a material used in arc tubes for high intensity discharge lamps. Both the glass and ceramic phosphor substrates kept phosphor temperatures sufficiently low to meet the thermal efficiency targets and keep thermal color shift to well within a 3-step MacAdam ellipse.

OPTICS

The role of the fixture optics is to convert the emitted light from the LED to the desired far-field distribution. At minimum, the fixture optics must achieve a beam angle FWHM of ≤60° with ≥85% efficiency. Other factors such as visual appearance, cutoff angle, and total size were also considered.

Two approaches to the optics design were demonstrated. The first consisted of a metalized conical reflector and was intended for maximum efficacy. No attempt was made to hide the LED from direct view. The second approach was intended for best visual appearance and used three components: a conical reflector, diffuser, and trim.



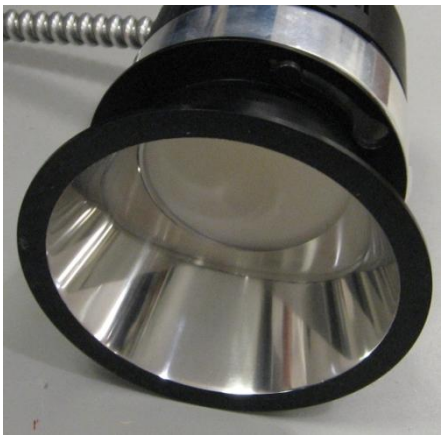


Figure 4. Photographs of the two approaches to luminaire optics. Metalized conical reflector (left) and reflector, diffuser, and trim (right).

Metalized conical reflector solution. A 5" diameter luminaire with integrated driver was fitted with this optic. The simple reflector optic achieved a 40° FWHM beam angle with 92% optical efficiency. The beam angle is within specification and the optical efficiency is significantly higher than the 85% budgeted. However, the bright LED source was exposed to direct view and the combination of the LED array and metal reflector resulted in an undesirable snowflake-like image of the chip array the far-field.

Conical reflector, diffuser, and trim solution. A 4" diameter luminaire with remote driver was fitted with this optics solution. The result was a 60° FWHM beam angle and optical efficiency of 80%. Efficiency was sacrificed, but the visual appearance was much improved. The yellow color of the phosphor was nearly imperceptible in the off-state and visible brightness or glare was greatly reduced by the diffuser.

LUMINAIRE RESULTS

Two downlight luminaire versions were tested: a 4" diameter with a remote driver and a 5" diameter with integrated driver. The downlights were powered with 120VAC at 60Hz frequency. Luminous flux measurements were made inside a 1 meter diameter integrating sphere after at least 90 minutes of operation time in order to reach a steady heat sink temperature. Luminaires were tested horizontally, which is not optimal for air flow over the vertically finned heat sinks.

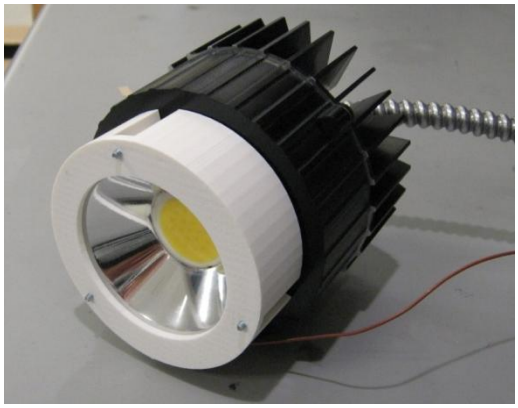




Figure 5. Photograph of 5" downlight with integrated driver (left) and 4" downlight (right).

Both luminaires incorporated an LED source of the type described earlier. At 25C with 280mA DC input, the LEDs averaged 100LPW efficacy, 1620lm flux, at 3500K with CRI of 82). The steady-state performance values and project goals are summarized in Table 3.

Table 3. Steady-state downlight performance compared to project goals.

	Luminaire efficiency	Efficacy (lm/W)	Flux (lm)	Power (W)	CRI
Project Goal	73%	70	1300	18.6	80
5" downlight	83%	82	1439	17.5	82
4" downlight	72%	71	1335	18.8	83

The 5" luminaire achieved an impressive 1439lm of flux and efficacy of 82LPW at steady-state. Luminaire efficiency (product of electrical, optical, and thermal efficiencies) was 83%, significantly exceeded the goal of 73%. Two factors contributed to this difference. First, the simple reflector optic resulted in loss of only 7-8%, not the 15% originally planned. Second, the luminous efficacy actually increased by 1% as the luminaire warmed up. The dominant reason for this was a drop in forward voltage of the LED chips, not spectral shift or change in driver efficiency. Luminous flux decreased by about 5% compared to 25°C, but this was offset by a reduction in power consumption as the LED voltage dropped.

The 72% luminaire efficiency of the 4" downlight was somewhat lower than the 5" downlight due to the differences in optics efficiency. This luminaire contains a diffuser and trim to deliver high quality light with appealing lit and unlit appearances. Luminous efficacy and flux values of 71LPW and 1335lm, respectively exceeded project goals. The luminaire efficiency only missed the project goal by 1%.

For both luminaires the CCT was within the ANSI 3500K chromaticity parallelogram and remained within a 3 step MacAdam ellipse of the chromaticity at 25°C. CRIs of 82 and 83 did not change with luminaire temperature and met the ≥80 specification.

As an initial stability test, the 5" downlight was run continuously for 1600 hours. Luminous flux and efficacy actually increased significantly during this period, while chromaticity remained constant. Results are shown in Table 4. While no claims of lifetime can be extrapolated from the test, it the LED and optics remained stable.

Table 4. 5" downlight performance before and after 1600 hour test.

	Luminaire efficiency	Efficacy (lm/W)	Flux (lm)	Power (W)	CRI
Project Goal	73%	70	1300	18.6	80
5" downlight	83%	82	1439	17.5	82
After 1600 hours	83%	87	1490	17.2	82

Finally, it is useful to compare the results from these two luminaires to similar alternatives already on the market. Input power, luminous flux, efficacy, and optics efficiency are shown for an existing CFL and LED downlight in

Figure 6. The 5" downlight was optimized for efficiency with little attempt to conceal viewing of the bright source, so it is not directly comparable to the existing solutions. The 4" downlight has comparable degree of source hiding to the existing solutions, with twice the efficacy of the CFL solution (but with 500 fewer lumens), and 87% higher efficacy than an architectural grade LED downlight (while nearly matching the flux). Both the existing CFL and LED solutions suffer from low optics efficiency, causing a loss of roughly half of the source luminous flux. The 4" luminaire proves that it is possible to have high luminous efficacy without sacrificing a visually satisfying lit appearance.



Figure 6. Comparison of existing downlight solutions (1 and 2) with downlights from this work (3 and 4).

CONCLUSION

The primary project goal of achieving a downlight luminaire with 1300lm flux and 70LPW efficacy at steady-state was achieved. Even better, it was achieved with a luminaire with a glare-reducing diffuser and trim optics for excellent visual appearance and quality of delivered light. If glare and visual appearance of the luminaire can be sacrificed, even higher performance can be obtained 1439lm, 83LPW at steady-state.

Both a new driver and high power LED were developed specifically for these luminaires. The high power LED source was developed that achieves up to 101LPW and 1702lm at 0.28A/mm^2 or 69LPW and 4831lm at 1A/mm^2 at a CCT of 3500K with CRI >80. The driver delivered 18.6W of power with efficiency >90%, PF >0.99, and THD <10%.

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