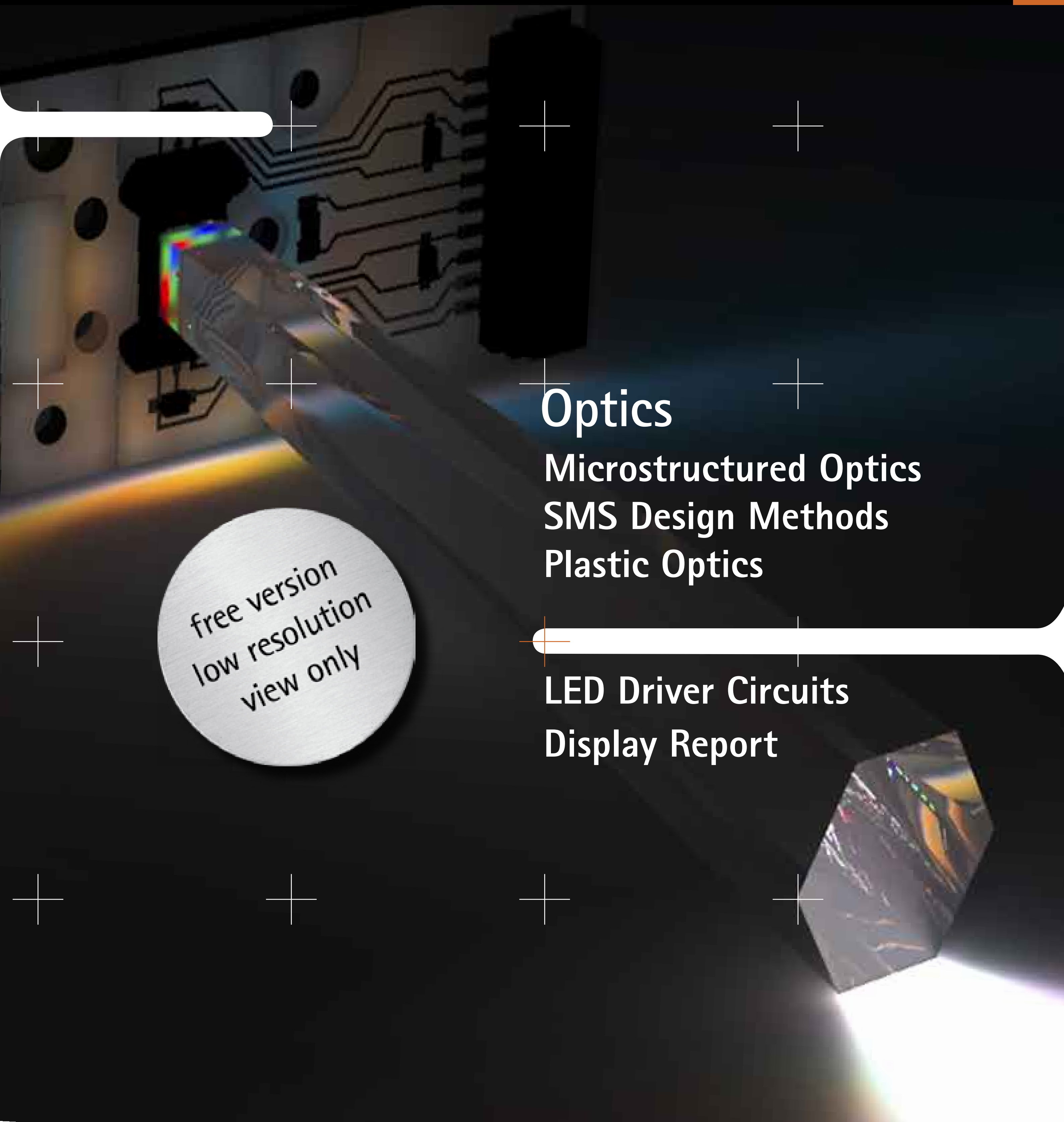
LED professional Review

www.led-professional.com
ISSN 1993-890X
LpR

The technology of tomorrow for general lighting applications.

Sept/Oct 2008 | Issue 09



Optics

Microstructured Optics
SMS Design Methods
Plastic Optics

LED Driver Circuits
Display Report

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More information about the company's diverse products and solid-state lighting solutions can be found at www.everlight.com

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Design of LED Optics

There are over 20 billion light fixtures using incandescent, halogen, or fluorescent lamps worldwide. Many of these fixtures are used for directional light applications but are based on lamps that put out light in all directions. The United States Department of Energy (DOE) states that recessed downlights are the most common installed luminaire type in new residential construction. In addition, the DOE reports that downlights using non-reflector lamps are typically only 50% efficient, meaning half the light produced by the lamp is wasted inside the fixture.

In contrast, lighting-class LEDs offer efficient, directional light that lasts at least 50,000 hours. Indoor luminaires designed to take advantage of all the benefits of lighting-class LEDs can exceed the efficacy of any incandescent and halogen luminaire.

Furthermore, these LEDs match the performance of even the best CFL (compact fluorescent) recessed downlights, while providing a lifetime five to fifty times longer before requiring maintenance. Lastly, this class of LEDs reduces the environmental impact of light (i.e. no mercury, less power-plant pollution, and less landfill waste).

Classical LED optics is composed of primary a optics for collimation and a secondary optics, which produces the required irradiance distribution. Efficient elements for primary optics are concentrators, either using total internal reflection or combined refractive/reflective versions. Secondary optics for homogeneous illumination of circular, square or oblong areas, or line foci is based on e.g., the honeycomb condenser principle, microlens arrays, etc. The design goals are high system transmission, minimum loss of etendue, reduction of straylight and a very short system length compared to conventional illumination schemes. Étendue, as a dominant optical design criterion, is the product or multiplication of the area of the emitter surface and the projected solid angle that the rays from the surface diverge into, and the units are mm^2-Steradians. This is a three dimensional version of the Lagrange invariant from imaging or conventional lens design.

The losses associated with secondary optics vary depending on the particular element used. Typical optical efficiency through each secondary optical element is between 85% and 90%.

Traditional optical design is based on ray tracing or aberration theory. Ray tracing is essentially a sampling technique in which data for a few rays are extrapolated to indicate the performance of an entire system. Aberration theory provides a different type of sampling, in which low-order performance coefficients are balanced with high-order performance coefficients to establish overall performance.

The September/October 2008 *LED professional Review (LpR)* issue highlights LED optics and points out how these technologies and methods can be applied in modern LED lighting systems.

We would be delighted to receive your feedback about *LpR* or tell us how we can improve our services. You are also welcome to contribute your own editorials.

Yours Sincerely,

Siegfried Luger

Publisher

Imprint

LED professional Review (LpR)

ISSN 1993-890X

Publisher

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Front-page picture

Mixing Rod/ Optical Research Associates (www.opticalres.com); provided by OEC

LED professional Review (LpR) – Subsription

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Next LpR Issue - Nov/Dec2008

- LED System Simulation and Testing

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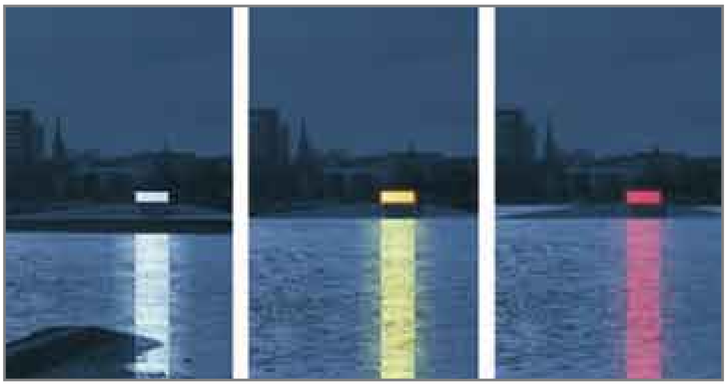
Project News

Semperlux and Vossloh-Schwabe Illuminate High Water Pumping Station

Cologne has been graced with a new landmark: the high-water pumping station in the Bayenthal suburb of the city. The pumping station is already a sight to see during the day thanks to its architectural aesthetic, which includes an organically landscaped area that inconspicuously tucks the structure into the banks of the Rhine. The control building, which was designed by the architectural company Kasper Kramer (BDA) to feature a contemporary metal grid façade, was kept prominent as the visible face of the facility. The breathtaking illuminations concept developed by the Semperlux lighting technology specialists in Berlin ensures the pumping station lights up in one of three colours depending on the water level of the Rhine. A normal watermark is indicated by white light, rising water levels by amber and on reaching the high water mark, the light turns red. The station then begins pumping off the discharge in the reinforced conduits. As a result, the citizens of Cologne are not only aware of when the pumping station is at work, but can also enjoy the eye-catching light spectacle as a thing of simple beauty.

Vossloh-Schwabe Optoelectronic provided the LED technology that made the artistic aspirations of this unique illumination system possible. Project decision makers opted for the LED solution for several reasons. Next to low energy consumption, high light output and flexible light control (thanks to RGB technology), LEDs guarantee an extremely long service life, practically no maintenance and, with that, very low life-cycle costs.



Different appearance of the pumping station from a distance view .

To suit this specific project, a system was developed that involved encapsulating standard VS Optoelectronic Flex modules fitted with SMD LEDs inside the aluminium sections of the metal grid façade. The white, red, green and blue Flex line modules, each backed with self-adhesive tape, were first precisely trimmed to fit and then fixed within the inside face of the respective segment. The LED modules were also specifically adapted to ensure even light-point spacing and uniform light density over the entire building. With the fitting order of the modules having been precisely calculated by the light engineers at Semperlux, actual installation was problem-free thanks to the highly flexible nature of the LED modules. Finally, the standard Flex modules were permanently encapsulated within the metal sections using a transparent potting material to ensure protection against environmental factors. The indirect LED lighting system works by light hitting the walls of the building and then being reflected to appear as an evenly illuminated surface. In response to the actual water level of the Rhine, a DALI unit triggers the respective light scene and a EUTRAC® DALI LightComposer®-REG module enables overall system control. As a result, both the citizens of Cologne and visitors to the city can enjoy these special illuminations night after night. ■

The pleasing daytime look of the high-water pumping station is only topped by the 'wow factor' that nightfall brings.

Product News

IST Launches High Efficient LED Downlights

Integrated System Technologies Ltd, a UK designer / manufacturer of LED systems and the industry leading iDrive range of LED drivers, has launched the first high-powered LED downlight range that is capable of replacing CFL fixtures. The patented DL-0x0 LED downlights are available in cool 5500K CCT and neutral 4100K CCT colour temperature options. This range of fixtures offers outstanding performance and a direct alternative to a twin 26-watt compact fluorescent downlight.

Patented DL-0x0 LED downlights.

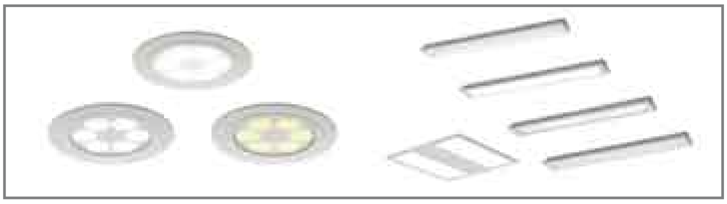
The light engine lamp lumens for the DL-090 was independently measured at 1060 lumens and the DL-080 at 963 lumens. These figures were calculated after the light engine had been running for 1 hour and measured in an integrating sphere. The LOR (Light Output Ratio) for the system is 0.89, which exceeds any traditional lighting product on the market. The power consumption is around 20 circuit watts which means the DL-080 downlight exceeds 40-lumens-per-watt system efficiency and the DL-090 exceeds 45-lumens-per-watt system efficiency. For the highest output options, the average Lux levels for the DL-080 are 2170 at 1m, 545 at 2m and 242 at 3m. The highest option DL-090 provides 2270 x at 1m, 567 x at 2m and 252 x at 3m. There are three cover options which include the standard diffuser, drop, and an option without diffuser. In addition, gold and chrome bezel finishes can be ordered instead of the standard white finish.

The DL-0x0 range has been developed to offer a true alterative to a twin 26-watt CFL downlight. As a starting point, IST purchased and independently tested a twin 26 watt CFL downlighter at the Photonics Cluster (UK). It was found that the CFL consumed around 68 watts of input power. The lamp lumens were rated at 3600. When tested in an integrating sphere, it only emitted 1750 lumens. This meant the true LOR was 0.49. In addition, IST found that the LUX levels were 2000 at 1m, 500 and 2m and 200 at 3m. These figures were used to produce an LED downlight equivalent.

Reliability is guaranteed as IST offers a 5-year warranty, making the new DL-0x0 range extremely attractive to high-end developers, high profile public buildings, and exclusive hotels. For applications where lighting is used for approximately 12 hours per day, the return on investment is estimated at 2-2.75 years. For applications with 24 hours operation, the return on investment is estimated at 1-2 years. The variables are dependant upon the volume of downlights per application. ■

Sharp to Introduce 11 LED Luminaries

Sharp Corporation has developed a series of new LED Lightings, including the "oblong" type that features a brightness equivalent to the fluorescent lamp fixtures*1 that are currently the main lighting in factories, offices and commercial spaces, and the "downlight" type with a brightness equivalent to a standard 150-watt incandescent light lamp. Sharp will introduce a total of 11 models into the Japanese market, including four oblong, one square, and six downlight models.



Some of Sharp's new LED luminaries.

Today, looking at a breakdown of the amount of electric energy consumed by lighting in Japan, business and commercial applications typified by factories and offices consume roughly double the amount used for residential home use. Thus, there is increasing demand for replacement lighting options with a view toward switching to the next generation of lights that offer high environmental performance and which do not use hazardous substances such as mercury.

LED lights, which have low energy consumption compared to incandescent lamps and fluorescent tubes, and which feature outstanding environmental performance including a long product life and being mercury-free, are expected to serve as the next generation of lighting sources. Sharp has been involved in the development and commercialization of LED devices for more than 30 years. Sharp has been working to take full advantage of its know-how nurtured over that time to enhance the brightness of these devices and assemble them into modules in order to develop new lighting fixtures, undertake mass production, and bring new LED Lightings to the marketplace.

The "oblong" lightings being introduced at this time feature an elongated form factor and deliver brightness equivalent to conventional fluorescent light fixtures equipped with twin 40-W straight-tube fluorescent lamps thanks to a luminaire efficacy of 74 lumens/watt, the highest in the industry for LED lighting. They also offer a high level of energy efficiency, consuming about 25% less power than conventional fluorescent fixtures. Both the oblong model and its companion "square" type model, which is ideal for conference rooms and reception areas, provide even, uniform illumination thanks to diffused surface-emitting light technology. Further, the "downlight" line-up includes a model with light output equivalent to a conventional 150-watt incandescent bulb, the highest brightness in the industry for LED Lightings. These downlight models are suggested for use in commercial spaces such as shopping centers and department stores, as well as hotel lobbies and entrance foyers to business offices.

LED Lightings manufactured by Sharp will be adopted as the main lighting in all plants to be located within the "Manufacturing Complex for the 21st Century" now under construction in Sakai City, Osaka Prefecture, and scheduled to begin operations by March of 2010. This will represent the world's largest collection of LED Lightings installed in buildings on this scale. Using this achievement as a springboard, Sharp will be working in the future to further expand its LED lighting business into factories, offices and commercial spaces around the globe. ■

New Alien LED Downlight™ from Martin Architectural

The Alien LED Downlight™ is a plug-and-play recessed LED downlight that features RGB+W color mixing and is available in a standard or high power version. Designed for accent lighting in colored or variable white light, the Alien LED Downlight's IP67 rating means it's equally suited to both indoor and outdoor environments.

The new Alien LED Downlight™ plug-and-play recessed LED downlight.

The Alien LED Downlight can be mounted on walls or ceilings and is ideal for expressive background lighting in restaurants, cafés, bars, small clubs and lounges. It is useful for wall grazing, as decorative accent lighting and niche lighting, or for bottle or product displays. The Alien LED Downlight is also perfect for entrance lighting or orientation lighting for marking columns, aisles, walkways, steps, and architectural features.

The Alien LED Downlight's RGB+W diodes excel at creating a broader range of hues including deep, saturated colors. The addition of the white LED gives several advantages: a true white, the ability to adjust color temperature, and the possibility to create soft pastel shades.

Colors are evenly mixed when leaving the fixture, making for an attractive looking luminaire. The Alien LED Downlight is 0-100% dimmable for balance of brightness or the ability to respond intelligently to the availability of natural light.

The Alien LED Downlight is available in two versions to cover a wider range of applications; a 9 W standard version (5 LEDs) and an 18 W high-power version (9 LEDs). Very bright when compared to other products in its class, well-known Rebel LEDs are used to ensure high performance and output as well as a high quality. Because lamp replacement isn't every 3000 or 5000 hours, no service is required other than regular cleaning.

For even greater flexibility in design, two optical systems are available, medium or wide, covering distances from approximately 0.5 to 3 meters (2 to 9ft).

The required Alien LED Driver, sold separately, is a plug-and-play unit that offers great flexibility for solutions using both 9W and 18W fixtures. One Driver can control up to a maximum of 20 standard luminaires or 10 high-power luminaires, or a combination of the two.

The Alien LED Downlight will fit into any standard MR16 hole, allowing it to blend inconspicuously into existing architecture and making it ideal as a replacement product or for new installations. Alien LED Downlights are easily interconnected by linking transformers together with standard IEC connectors.

The Alien LED Downlight has two DMX control modes, HSI & RGBW for comprehensive control when a designer needs it. The intuitive HSI control system allows designers to control the unit in terms of color rather than only DMX levels. A stand-alone feature offers 31 pre-programmed static or dynamic sequences via the Alien Driver Unit.

The Alien LED Downlight is made of a durable steel and aluminum construction and the IP67 rating means it's fully weather-protected. It comes with stainless steel trim rings as standard with chrome, white or brass available as accessories.

The luminaire is convection cooled so no fans or other moving parts are used. Rigorously tested and CE, ETL & CETL approved, the Alien LED Downlight is built for simplicity. ■

Tri-O-Light Casting Resins: Freedom to Sculpture

The light line in the street in front of the entrance to the Gelredome stadium (Arnhem, The Netherlands) is one of the projects which have been realized with the LED Light Strip RGB of Tri-O-Light and the polyurethane casting resin technique of Multicol casting adhesives trading: a new expertise within Tri-O-Light. In addition, the casting resins were used as FLEXLED, indirect LED lighting underneath benches in a shopping centre in Amsterdam, and the bus stop "Arena Boulevard", as well as curbstone lights on several roundabouts in the Netherlands.

Conformed to the wishes of the client, a flexible, diffuse RGB LED-light line has been developed, which is water resistant, flexible, durable and of high impact. The colour of the 60m-long light line can change and is controlled from the reception area of the stadium. For every event, the correct colour adjustment is shown using the DMX control panel. The light line was supplied in six prefab parts and glued into the ready made compartment. The flexibility of the material allows the light line to be inserted in a radius.

Multicol is the right partner for the production and distribution of a large selection of highly developed types of adhesive for the industry. It also handles pouring products in a casting resin for numerous applications.

Project examples for Tri-O-Light casting resins.

In a state-of-the-art equipped lab, Tri-O-Light disposes of the newest casting resins, such as transparent polyurethane casting resins. They pour fixtures to the customer's requirements. In this chosen fixture, LED lighting is built. Thanks to the advanced pouring process, the customer or the designer has the possibility to develop products following their own design. All casting resins are solvent free, transparent and extremely suitable for outside applications.

The properties of the polyurethane castin resin can be adjusted by Tri-O-Light's specialists, ranging from very hard and rigid to very flexible. The colour can also be adjusted, from transparent to diffused. And the resin itself can also be coloured. ■

ALBEO LED High Bay Delivers Maintenance-Free Lighting

Albeo Technologies released its Constellation series LED High Bay luminaire for industrial, commercial, warehouse and retail spaces. Albeo is the first LED light fixture manufacturer to make an LED fixture that combines the reliability of LED lighting with the fixture performance requirements for high bay applications.

Maintenance of high bay lighting is expensive: the lamps don't last long; they require a lift to service; and they are frequently placed over operating machinery, public areas, or sensitive material. The high cost of changing lamps and ballasts puts a premium on fixture longevity, and now the Constellation LED High Bay provides high bay performance with over 50,000 hours of operating life. When combined with Constellation's 20,000 lumen output and 360 watt maximum power consumption, the LED High Bay provides a compelling business case for one-for-one replacement of metal halide or high bay fluorescent fixtures. The economics of Constellation can be further enhanced with the use of the optional motion sensor or off-the-shelf daylight sensors.

The Constellation series LED High Bay luminary.

"Solving our customers' energy, maintenance, and environmental problems drives Albeo's creative process," said Jeff Bisberg, CEO. "Our deep electro-optical design capabilities have allowed us to lead in the industrial LED marketplace with the first dedicated industrial high bay fixture. Our new trial program now enables customers to test this leading-edge solution and accurately evaluate the business case for a switch to LED lighting."

In addition to best-in-class performance and lifetime, Constellation High Bay customers will be able to enjoy the many associated benefits of LEDs, including:

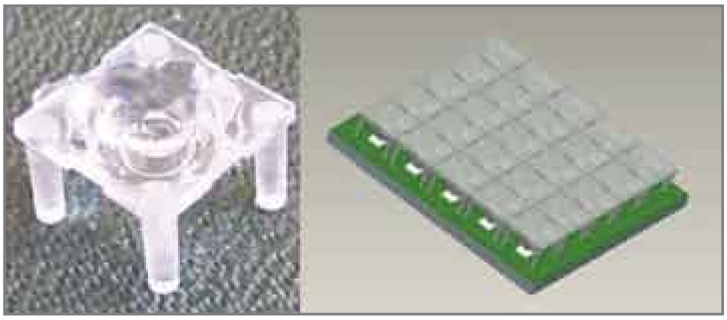
- LEDs run cooler than traditional fixture types, reducing air conditioner loads
- LEDs are fully dimmable and compatible with various controls
- LEDs contain no hazardous mercury, so they do not require recycling
- LEDs are nearly unbreakable
- LEDs are free of annoying flicker and buzz
- LEDs are safer, operating on low voltage DC, with no glass or vacuum

Because LED lighting is new to general illumination, particularly high bay applications, Albeo has created a trial program for users to test the fixtures in their own building. The Albeo trial program allows customers to test a sample of fixtures for 60 days with no risk. ■

New Polycarbonate Optics from Carclo

Carclo Technical Plastics announces the immediate availability of a wide range of high performance polycarbonate optics to manage the light output from new Cree XLamp® XP-E and XP-C LEDs.

These new optics are available immediately in 10mm square "small footprint" optics, and soon in standard 20mm and 26.5mm diameter sizes, in both a clear and a frosted finish. The 10mm optics feature a clear medium beam with a FWHM (Full Width Half Maximum) beam angle of 16.4 degrees, an elliptical or "line" optic with a 43x16 degree beam, as well as Carclo-exclusive frosted optics in medium (18 degrees FWHM) and wide (26 degrees FWHM) beams. Carclo 10mm "small footprint" optics do not require a separate holder, and can easily be grouped together in square, rectangular or linear multi-LED arrays.



Carclo 10mm optic and model of multi-LED array.

Carclo also wishes to announce the immediate availability of a 20mm side-emitting optic for the Cree XLamp® XP-E and XP-C LEDs, with an industry-leading 5-degree beam angle around a full 360 degrees, and efficiencies approaching 90%. Finally, 20mm and 26.5mm optics for the new Cree XLamp® XP-E and XP-C LEDs will soon be available in narrow, medium and wide beam angles, in both clear and Carclo-exclusive frosted optics, as well as elliptical and elliptical orthogonal line optics.

Ian Bryant, Business Development Manager for Carclo's UK optics business, said: "Cree XLamp® XP-E and XP-C LEDs have been developed by Cree for lighting-class performance in a small-footprint, low-profile LED package, and to give LED lighting designers enhanced flexibility and performance to further accelerate the LED lighting revolution. We are delighted to be able to offer a line of optics to coincide with the launch of these new LEDs." Jim O'Connor, Business Development Manager for Carclo USA added: "Carclo's timely announcement of a wide range of optics for the newly introduced Cree XLamp® XP-E and XP-C LEDs is a further indication of Carclo's firm desire to support users of new LEDs developed by all the major manufacturers. We believe that our unique 10mm small-footprint optics and our Carclo-exclusive frosted optics will provide the kind of performance that will allow these new LEDs to be rapidly incorporated into new designs for LED light engines and solid state lighting fixtures." ■

Cree: New XLamp® XP-E and XP-C LEDs

Cree, Inc. announces a new standard for lighting-class LEDs with the introduction of the XLamp® XP-E and XP-C LEDs. These breakthrough LEDs have the smallest footprint in the industry for lighting-class LEDs—providing the same high-quality lighting performance and proven reliability as Cree XR-E and XR-C LEDs in an 80% smaller package.

The new XLamp LEDs, measuring just 3.45mm square by 2mm high, can enable new applications, including backlighting, signage, outdoor, indoor and portable lighting, thanks to their small size and low profile as well as a wide viewing angle and symmetrical package. Available bins for XLamp XP-E LEDs include minimums of 100 lumens at 350mA in cool white (5000K - 10000K) and 80.6 lumens at 350mA in warm white (2600K - 3700K).

Small footprint high power LEDs: XLamp® XP-E and XP-C LEDs.

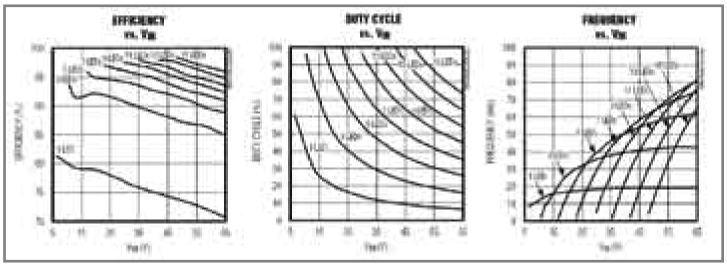
"We recognized an unmet need for lighting-class performance in a small-footprint, low-profile LED package. These products, based on an innovative new technology platform, address this need," said Paul Thieken, Cree marketing director for LED components. "This new platform, in concert with the existing XLamp products and the recently demonstrated XLamp MC-E LED, give LED lighting designers enhanced flexibility and performance to further accelerate the LED lighting revolution." ■

Maxim: High-Efficiency HB LED Drivers for Greener Lighting Solutions

Maxim Integrated Products introduces the MAX16822A/B and MAX16832A/C family of 2MHz, high-brightness (HB) LED drivers with an integrated MOSFET and high-side current-sense circuitry. These highly integrated devices reduce the size, complexity, and cost of solid-state lighting (SSL) designs, simplifying the implementation of green lighting technology. Moreover, they provide the high conversion efficiency and advanced thermal-management capabilities critical to LED system designs. The MAX16822A/B and MAX16832A/C are ideal for MR16, MR111, and other architectural lighting applications, as well as front and rear automotive lighting (RCL, DRL, and fog/low-beam lights).

These high-voltage, switch-mode HB LED drivers are capable of delivering over 18W (MAX16822A/B) or 36W (MAX16832A/C) of output power with up to 95% efficiency, while driving as many as 15 white LEDs in series. The MAX16822A/B can deliver up to 350mA of continuous DC current, while the MAX16832A/C can deliver up to 700mA of continuous DC current to the LED string. These devices offer an analog dimming feature that allows the LED current to be controlled by an external DC voltage and PWM dimming input for a wide range of brightness levels.

These HB LED drivers require only a few external passive components for the design of a low-cost LED driver circuit. By integrating a 65V switching MOSFET with RDSON values of 0.85ohms (MAX16822A/B) and 0.45ohms (MAX16832A/C), they eliminate the need for an external power transistor. Additionally, high-side current sensing and integrated current-setting circuitry further reduce the number of external components required, while delivering ±3% LED current accuracy.



Typical Operating Characteristics (VIN = VDIM = 48V, CVCC = 1µF, RSENSE = 0.62Ω, L = 220µH;@ TA = +25°C).

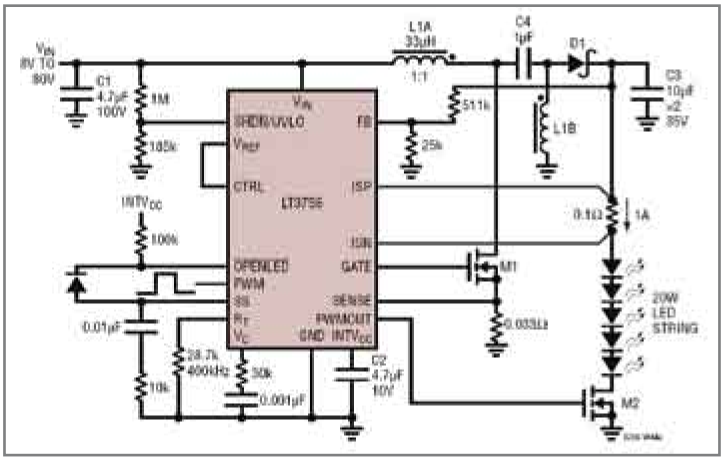
A hysteretic, step-down (buck) mode enables these devices to drive a long string of HB LEDs from input voltages as high as 65V DC. This control method renders control-loop compensation unnecessary, thus simplifying the design and minimizing component count. The MAX16822A/B and MAX16832A/C are designed to hold the LED current ripple to within 10% (A versions) and 30% (B and C versions) without the use of an output capacitor. Moreover, the devices support switching frequencies up to 2MHz, allowing the use of small-sized components.

The MAX16822A/B and MAX16832A/C integrate thermal-shutdown circuitry to protect the driver under excessive thermal conditions. Their 200mV, high-side current-sensing minimizes the voltage drop across the external sense resistor, thereby reducing power dissipation. Additionally, they provide analog thermal-foldback protection that reduces the LED current in conjunction with an external negative temperature coefficient (NTC) thermistor when the temperature of the LED string exceeds a specified limit.

This robust family of HB LED drivers operates from a 6.5V to 65V input voltage and is fully specified over the -40 degrees Celsius to +125 degrees Celsius automotive temperature range. The MAX16822A/B are available in a lead-free, 8-pin SO package, while the MAX16832A/C are offered in an 8-pin SO package with exposed paddle. Prices start at $0.99 for the MAX16822A/B, and $1.31 for the MAX16832A/C (1000-up, FOB USA). ■

100V, Full Featured LED Controller for High Current LED Applications

Linear Technology announces the LT3756, a 100V, high-side current sense DC/DC converter designed to drive high current LEDs. Its 6V to 100V input voltage range makes it ideal for a wide variety of applications, including automotive, industrial and architectural lighting. The LT3756 uses an external N-channel MOSFET and can drive up to 20 1A white LEDs from a nominal 12V input, delivering in excess of 70 watts. It incorporates a high-side current sense, enabling it to be used in boost, buck, buck-boost or SEPIC and flyback topologies. The LT3756 can deliver efficiencies of over 94% in boost mode, eliminating any need for external heat sinking. A frequency adjust pin permits the user to program the frequency between 100kHz and 1MHz, optimizing efficiency while minimizing external component size and cost. Combined with a 3mm x 3mm QFN or a thermally enhanced MSOP-16 package, the LT3756 offers a very compact 70-watt LED driver solution.



Design example for 90% Efficient, 20W SEPIC LED Driver.

The LT3756 uses True Color PWM™ dimming, delivering constant LED color with dimming ranges up to 3,000:1. For less demanding requirements, the CTRL pin can be used to offer a 10:1 analog dimming range. Its fixed frequency, current mode architecture ensures stable operation over a wide range of supply and output voltages. A ground referenced voltage FB pin serves as the input for several LED protection features, making it possible for the converter to operate as a constant-voltage source.

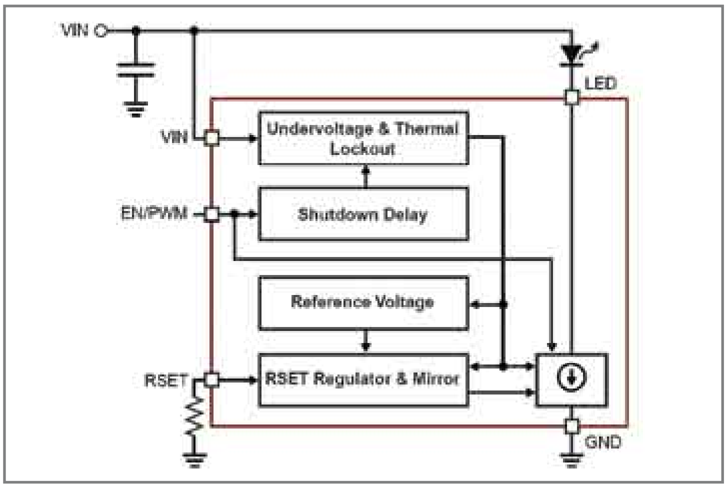
Summary of Features:
- 3000:1 True Color PWM Dimming
- Wide Input Voltage Range: 6V to 100V
- Output Voltage Up to 100V
- Constant-Current & Constant-Voltage Regulation
- 100mV High Side Current Sense
- Drives LEDs in Boost, Buck Mode, Buck-Boost Mode, SEPIC or Flyback Topology
- Adjustable Frequency: 100kHz to 1MHz
- Programmable Undervoltage Lockout with Hysteresis
- Open LED Status Pin (LT3756)
- Frequency Synchronization (LT3756-1)
- PWM Disconnect Switch Driver
- CTRL Pin Provides Analog Dimming
- Low Shutdown Current: <1uA
- Programmable Soft-Start
- Thermally Enhanced 16-Lead QFN 3mm × 3mm Package or MSOP-16E Package

Two versions of the LT3756 are available. The standard LT3756 offers an Open LED Status pin, and the LT3756-1 replaces the Open LED Status pin with a frequency synchronization pin. ■

Catalyst: 1A Constant-Current, Low Dropout Driver

Catalyst Semiconductor, Inc. a supplier of analog, mixed-signal and non-volatile memory semiconductors, has expanded its line of constant-current, LDD™ (low dropout driver) products to include a new, simple-to-use, high-power device for architectural, landscape, automotive and general LED lighting products. The CAT4101 is a linear-based, constant-current LED driver, which drives long strings of LEDs and provides a high-current solution for a wide range LED applications.

Product Features:
- 1A current sink with high accuracy
- Up to 25V operation on LED pin
- Low dropout voltage drive 500mV/1A
- LED current set by external resistor
- High resolution PWM dimming via EN/PWM
- Thermal shutdown protection
- Packaging: 5-lead TO-263



CAT4101 block diagram.

Since it is a linear-based LED driver, the CAT4101 does not require an inductor, eliminating noise, minimizing component count and simplifying design. The LED current is set via an external resistor connected to the RSET pin. The LED pin is compatible with high-voltages up to 25V. This enables the CAT4101 to drive long strings of up to 10 LEDs, adjustable to 1A. The device offers high-speed, high-resolution PWM dimming, an "instant-on" PWM control mode and thermal shutdown protection in the event of an over-temperature fault condition. The CAT4101 is available in a 5-lead, TO-263 package to provide exceptional thermal dissipation. ■

Ultra-Large 8" Sapphire Wafers for LEDs

Monocrystal, a leader in the synthetic sapphire and other advanced electronic materials markets, has announced that the company launched production of its ultra-large 8" C-plane epi-ready sapphire wafers for LED manufacturing in August.

The 8" sapphire wafer has 16 timest the face of a standard 2" wafer.

Monocrystal was able to rapidly ramp up production of the new generation sapphire wafers for LEDs by leveraging its superior technology for growing large sapphire crystals – the company has routinely produced large sapphire crystals that exceed 65 kg since late 2005. Another key factor that helped Monocrystal advance on 8" wafers for LEDs was its proprietary wafer fabrication technology developed earlier in spring for production of the new generation ultra-large 8" R-plane sapphire wafers for RFICs. Monocrystal already shipped its 8" wafers to LED and RFIC customers.

"Being first to market with our ultra-large 8" wafers for LEDs is a clear indication of Monocrystal growing brand's exposure and recognition, its expanding market and technology leadership," stated Vladimir Polyakov, Chairman of the Board of Monocrystal and President of Energomera, the mother company of Monocrystal. "To be successful in a hightech market, you should truly possess the capabilities of a technology leader, and be able to constantly innovate and offer products of the highest quality that meet the current and future needs of your clients. Monocrystal exports 90 percent of its production, and is a key supplier for LED and RFIC markets," he concluded.

Today, increasing demand for energy-efficient and "green" materials, products, and technologies is becoming a solid global trend. The introduction by Monocrystal of its ultralarge diameter sapphire wafers for solid state LEDs is a socially responsible contribution of the company to address growing global concerns of inefficient energy consumption, carbon emission, and use the of hazardous materials. ■

opsira: Spectroradiometer SPR'3

The new conceptional design of opsira's spectral measurement systems is aimed at developing a portable system for absolute spectral emission measurements from UV to NIR.

Portable Opsira Spectroradiometer SPR'3.

The SPR'3 system's scope of application includes the measurement of light sources, lamps and optical systems within a wavelength band of 200 to 1100 nm. The measurement of the absolute spectral emission provides very high accuracy for the measurement of monochromatic light sources, as well, for example with LEDs. The measuring scale can even be enlarged and radiation prefiltered by an integrated filter wheel using any filter you choose. A Spectrometer and absolute sensors form a compact unit. A USB interface provides a simple data connection to any computer or laptop.

The total calibration information is stored on the sensor head. Thus the system can be operated by different computers. The robust system works without external optical fibre and, therefore, can also be used in a rough environment. The control and evaluation software was redesigned and offers a variety of analysis methods. Emission, reflection and transmission measurements round off the scope of performance of the SPR'3 measurement system.

opsira GmbH delivers the SPR'3 unit completely calibrated and also provides the recalibration service. ■

IP News

OSRAM and Philips Conclude LED Cross-License Agreement

LED luminaire manufacturers can now use key components from OSRAM without having to pay license fees to Philips because OSRAM has acquired special rights from Philips. Luminaire manufacturers are therefore released from the costs resulting from the LED luminaire license program recently published by Philips.

The special rights relate not only to patents held by Philips but also to patents held by Color Kinetics and TIR Systems which were acquired by Philips last year. The compensatory payment – which both parties have agreed not to divulge – will be partially offset by OSRAM by selling rights to its own patents. This agreement will give the market for LED-based lighting a further boost.

"Thanks to this agreement, OSRAM key components provide our customers with unique opportunities. It stimulates new possibilities for the lighting market and, like Philips, we will accelerate the development of this market", said Martin Goetzeler, CEO of OSRAM. The LED components are based to a large extent on chips fabricated in OSRAM's highly advanced factories in Regensburg and Penang/Malaysia, and this is an area in which OSRAM itself has a leading patent portfolio. ■

Edixeon® ARC Series

High Power LEDs

- Fully Integral Design
- Various colors
- More energy efficient than incandescent and most halogen lamps
- Low voltage operated
- Instant light
- Delievered as usual

With the diverse applications of LED, the emerging SSL market also demands for higher luminous flux and efficacy of LED. Edison Opto, a Taiwan based high power LED packaging manufacture, has introduced ***Edixeon® ARC series, a production-ready,100lm packaged light source*** to its high power LED Edixeon® family. Driven at 350mA, Edixeon® ARC series is the first of its kind to truly achieve luminous efficacy over 100lm/W at cool white LED (CCT: 5,000K~10,000K).

1LS5 1W 100lm

3LS5 3W 170lm

Edixeon® ARC series is IR-Reflow compatible and is also available in warm white (CCT: 2,670~3,800K) and neutral white (CCT: 3,800~5,000K) with luminous flux reaching 60lm for warm white and 75lm for neutral white respectively. Edixeon® ARC series is ready for shipment by October.

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Progress in LED and OLED Display Technologies

> M. Nisa Khan, Ph.D., President, LED Lighting Technologies

No one doubts that numerous challenges are preventing LEDs from becoming ubiquitous in the general illumination market. However, the illumination industry leaders see this as a possibility over a 10-year horizon, if not sooner. Already LEDs have overtaken in traffic lights, some automotive head and rear lights, channel letters in signage, and in some architectural lighting applications. In most of these applications, inorganic III-V compound semiconductor LEDs are favored and OLEDs are considered less-mature counterparts, at least for some time.

While LEDs are not yet the overwhelming choice in various lighting and other illumination markets, they are very popular in billboards and various other large-format indoor and outdoor displays. Their large viewing distances allow for coarse resolution or pitch, which can be achieved with individual RGB packaged-LEDs placed in proximity. These LEDs are mostly the more mature inorganic III-V semiconductor LEDs.

However, when it comes to smaller screens requiring much higher resolutions as in consumer electronics namely cell phones, cameras, various other handheld devices, prototype laptops and television screens, OLEDs have been the choice over the III-V LEDs. Why?

The reason is that a planar array or uniform, high-quality LEDs in very close proximity needed to form a high-resolution viewing screen is not possible with III-V semiconductors over too large an area. The reasons are multifold. First, high-quality RGB LEDs need to come from different III-V compound materials and therefore monolithic integration of 3-color pixels in a single flat plane is not feasible. A hybrid integration of inorganic RGB LEDs with 16micron pixel pitch with adequate color isolation (16 micron pitch is needed to achieve 160 pixels per inch, required in 1920X1200 WUXGA laptop screen; 1micron = 1/1000cm) is surely a daunting task. Even if these RGB pixels could be constructed in a III-V plane, it would be limited by the 2-inch standard wafer size in this industry. As of now only a few high-end LED manufacturers have 3-inch or 4-inch wafer processing capability, which is still rather small for display technologies. Furthermore, single-color LEDs processed in a wafer are subjected to such significant challenges as non-uniformity, impurities, dislocations, and lithographic variations, all of which lead to the well-known 'binning' issue. These challenges are particularly pronounced at the edge of the wafers, making a good portion of a wafer unusable. Even if III-V RGB LEDs, say, could be produced over an area as large as one square centimeter using some flip-chip wafer bonding technique, tiling them to create a small cell phone screen is also unlikely because of an evitable tiling gap of at least 1/100 of an inch would still be unacceptable.

The OLEDs on the other hand are fabricated using a method similar to ink-jet printing. This method can precisely deposit, with sufficient isolation, organic RGB molecule dye chemicals or predetermined emissive polymers into miniature wells fabricated in organic layers. The RGB well combination forms a pixel in passive or active matrices known as PMOLED or AMOLED displays that can provide beautiful colors. The repeatable chemical fabrication process along with monolithic integration of organic layer transistors (TFTs) allow for superior OLED color display and video processing. One of the latest OLED breakthroughs has been a 31-inch TV prototype from Samsung SDI shown in CES 2008 in Las Vegas; this 1080p panel, just 4.3mm thick, uses half the power of a "typical" 32-inch TV. Their 2005-version was a 21-inch OLED display featuring the highest WUXGA resolution with 6.22 million pixels. They both adopted the AMOLED technology for its low power consumption and high-resolution qualities. The screens have brightness of 400 nits, contrast ratio of 5000:1, color gamut over 75% and fast response times, making them ideal for viewing HD-resolution video images. The best AMOLEDs can display almost four times as many colors as equivalent-size LCDs can produce with much wider viewing angles.

Samsung SDI (Figure 1) also boasted recently about their 12-inch AMOLED display-fitted notebook possessing a 1,280 x 768 resolution with all the usual benefits of this display technology. They claim a contrast ratio 20 times that of conventional LCD displays!

Figure 1: Samsung Demos OLED Display-Fitted Notebook - Photo: Courtesy www.electronista.com (May 16, 2008).

Despite the OLED promises, laptops, most cell phones, and other hand-held display devices predominantly use LCDs, a technology invented in 1963 with a hope to replace bulky CRTs. While OLEDs need further improvement in lifetimes, LCDs are difficult to scale up to large surfaces. LCD production and commercial expenses are still high and therefore remain vulnerable to new innovations.

Samsung, SONY, Osram, and Kodak are but a few big companies banking on OLEDs for various display applications. ISuppli Corporation believes by 2010 factories will be churning out 289 million AMOLED displays annually estimating that about 88% of them will end up in cell phones.

Today OLEDs are commercially used in limited quantity cell phones, cameras and car stereo displays because they are only on part of the time. Using them in computers and TVs may take another five years as companies work on developing longer-lasting chemicals.

Large-format displays viewed from much larger distances than those typical of consumer electronic devices can use larger pixels and lower resolutions. Inorganic LEDs are best-suited for them because these bright, robust, long-lasting and high-quality LEDs can be packaged as surface-mounts and be integrated on a mother-board with drive electronics, with a pixel pitch as little as 4 mm. Such pitch-size or greater is appropriate for large-screen indoor and outdoor displays found in billboards, stores, malls, theatres, and on-premises of town plazas. High-brightness combined with dynamic color and resolution options make these large LED displays superior to other display technologies.

One must however regulate a number of elements to maximize viewing quality when using LED display panels. These are screen resolution, brightness and contrast, video processing, electrical usage and maintenance.

Screen Resolution

Resolution is the key to a quality image on a large-format video display. It is defined by the total number of vertical and horizontal pixels that form the picture. The picture on the screen is typically reproduced from a video signal that have a native NTSC resolution of 486 (vertical) X 240 (horizontal) or 576X720 (PAL). A screen with fewer pixels than the input video signal will have less resolution than the source; for best results, a minimum resolution of about 648×486 (NTSC) or 768×576 (PAL) is recommended; however, a properly designed display with lower resolution can still give an acceptable appearance for video images, like those seen in a standard VGA screen. Taking this as a benchmark, to achieve the same 640×480 VGA (15-inch diagonal) resolution with a 3m × 2.25m screen, the pixels would need to be spaced approximately 4.5mm apart. This distance between pixels is called pixel pitch, measured usually in millimeters.

Typically, indoor-screen pixel pitches are 6mm, 10mm, 16mm, and 20mm, whereas 16mm, 20mm, 25mm, and 30mm are used for outdoor screens. Outdoor screens tend to be larger than indoor screens because the viewing distance is often greater. QS-tech (QS-tech.com), a Chinese manufacturer, now offers pixel pitches starting from only 4.4 mm for indoors and 10mm for outdoors. They will be one of the major suppliers for the 2008 Olympic Games in Beijing. Fig. 2 shows an LED billboard (6-mm pixel pitch) they delivered to the National Stadium in Beijing for the 2008 Summer Olympic Games.

Larger pixel pitch leads to higher pixelization meaning the viewer starts to see the pixel structure. Hence, the screen designer needs to calculate it based on the distance between the viewer and the screen. The choice is also dictated by any physical size constraints, sight lines, and of course, budget.

Figure 2: LED Billboard by QS-Tech delivered to the National Stadium in Beijing, China (Photo: Courtesy of QS-Tech).

When pixels are viewed up close, the RGB LEDs appear as separate dots. These LEDs mix to form a single color at a distance from the screen known as the color compound distance (CCD). For indoor displays, more advanced color compound scheme is required to make images appear clear and sharp from close range. Best indoor displays use 3-in-1 RGB in one packet with SMD LEDs, where as outdoor displays use individual RGB LEDs. Typically, CCD is calculated by multiplying the pixel pitch in millimeters by 250mm for indoors and by 500mm for outdoors. The minimum viewing distance is determined by multiplying the pixel pitch by 750 to 1,000. The maximum viewing distance is generally 20X to 30X the screen height.

Brightness & Contrast

Brightness, or more accurately luminance, for LED screens is measured in nits (cd/m^2) using a light meter. The general rule is to require at least 1,000nits for an indoor display and 5,000nits for outdoor displays. The designer first measures a full white signal at a normal angle to the screen, setting color temperature at 6,500K (D65) for outdoor screens, and 5,000K (D50) for indoor screens. He then repeats this measurement several times at various points (equally spaced) of the screen. Setting the screen to black, he then re-measures for the ambient reflected light. The brightness is an average of the various points of white, minus the measured ambient when the screen is black.

The viewing angle (VA) is defined at the point when brightness falls to 50% from the maximum value. By walking around the screen, the designer can determine how brightness changes, and review the RGB and white to see if the colors remain uniform at all angles. A challenge unique to LED display technology is known as shouldering, a color shift caused by one LED blocking the view of another at extreme angles. The VA should include color shifts as well as brightness; if a significant color shift occurs at an angle before the brightness falls by 50%, then VA is reduced to this angle.

Screen manufacturers should not drive the LEDs at high currents and quote impressively high brightness figures. High drive currents lead to faster degradation in the LEDs, leading to dramatic screen non-uniformity. Quoted LED screen lifetimes ranging from 20,000 to 100,000 hours are only meaningful if determined at the actual drive current used under real display conditions.

Video Processing

A standard video signal cannot be directly displayed on an LED screen without first processing it electronically. Many sophisticated electronics now exits for image processing. Video images are comprised of a number of horizontally scanned lines, but not all appearing on a screen simultaneously. In the first 1/60th of a second (1/50th for PAL), the odd lines are shown, followed by the even lines in the next 1/60th of a second, forming a complete frame. This familiar interlaced display is also used for television. For non-broadcast video signals, the signal is first de-interlaced.

Resolving video that involves rapidly moving objects requires sophisticated interpolation in real-time along with appropriate scaling to fit the output screen that normally has a different resolution from the source. These manipulations, especially the scaling, requires powerful processing to generate vivid, artifact-free, and fast-moving flicker-free video, generally done by dedicated video processing equipment. A standard step is to view the content first using a CRT TV monitor, although it is not always a true representation of how the picture will look on an LED screen. The PC world extensively uses DVI (Digital Visual Interface – transports material between devices through a refining process), which is overwhelmingly popular (90%) in LED installations, and also becoming a standard for A/V.

Electrical Usage and Maintenance

LED screen design and practices also include proper electrical adoptions and maintenance. It is important to have the appropriate circuit breakers to handle in-rush prior to switch-on, overloads, and earth leakage. Finally when an LED screens needs a repair, you need to ensure that right spare parts are available and that vendor service is adequate. When installed and configured properly, LED displays can be vibrant and exciting. By following these guidelines mentioned here, users can maximize results and avoid common pitfalls.

LED displays are already a huge market ranging from cell phones, cameras, car dashboard displays to large-format displays. Still we can expect a gigantic increase of these products worldwide in the near term. In the not too distant a future, we may also see OLED TVs and laptop screens as manufacturers work to increase their longevity. ■

Optics

Microstructured Optics for LED Applications

> Arthur Davis, Reflexite Optical Solutions Business

Abstract

Optics for use with Light Emitting Diodes are described. Microstructured optics are available and customizable for a wide variety of applications. A few of these will be touched on. A methodology of designing these optics and the photometrics of the typical technology is overviewed.

Introduction

With the increasing popularity of LED's in lighting applications, there is a need for engineered photometric control. Given exacting output requirements, it is unusual for a given supplier's LED to produce the correct emission profile. This can be remedied with the use of auxiliary optics. Available classes of optics include refractive (continuous surface and microstructured), reflective (continuous and facetted) and diffractive. Examples are shown in Figure 1. This paper will concentrate on microprism refractive optics with some mention of reflectors.

Figure 1: Common types of optics.

The type of designs considered here are light energy directing designs or "nonimaging optics". Some nonimaging design background will be outlined followed by mention of some specific LED commercial applications. Design methodologies for microstructured refractive optics will then be explored and a photometric analysis of a sample design will be presented. Finally a discussion on some salient issues regarding LEDs and microstructured optics is offered.

Background

Photometric plots

The required output specification is usually called out in photometric units: either Luminous intensity (lumens/steradian or lm/sr also known as candelas or cd) or Luminance (cd/m²). Sometimes Illuminance (lm/m²) is important (mostly for uniformity requirements).

Luminance is usually a calculated conversion from Luminous intensity (it can also be measured directly). Luminous intensity is a quantity commonly measured at photometric labs and a typical output from raytracing. The formula for converting from Luminous intensity to Luminance is:

$$L_v = \frac{I_v}{A_{vis}\cos(\theta)}$$

where L_v is the Luminance, I_v is the Luminous Intensity, A_{vis} is the visible area and θ is the Zenith Angle.

There are a variety of ways to represent the photometrics. Luminous intensity and Luminance can be represented on similar plot types. Useful representations are 3Dmesh, contour, polar, rectangular and Söllner.

3Dmesh is uncommon, but it can help as a method of visualizing what the photometric distribution is. It is done by plotting the Luminous intensity (or Luminance) magnitude in three dimensional coordinates. A 3Dmesh plot is shown in Figure 2 for a Luxeon LXHL-MW1A [1].

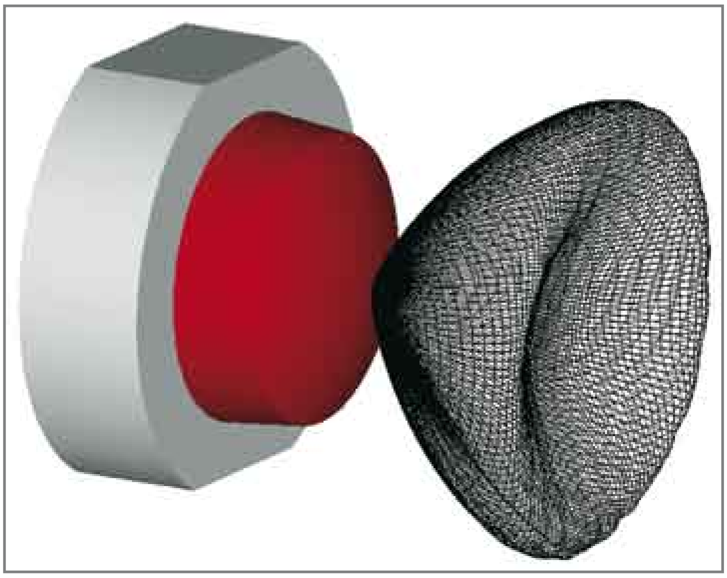

Figure 2: LED Solid geometry with 3Dmesh photometric "batwing" distribution (Luxeon LXHL-MW1A).

A contour plot is made by taking the hemisphere in which the light distribution emits and plotting the magnitude proportional to assigned colormap values on polar coordinates as shown in Figure 3. The rings of the plot are the zenith (or the angle from the polar axis) and the spokes are the azimuth (or the angle around the polar axis). See Figure 4 for the geometry of the coordinates.

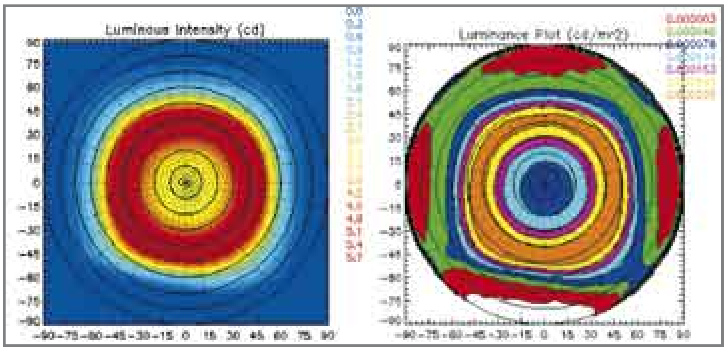

Figure 3: Contour plots for the photometric distribution shown in Figure 2. Left: Luminous Intensity. Right: Discrete level Luminance.

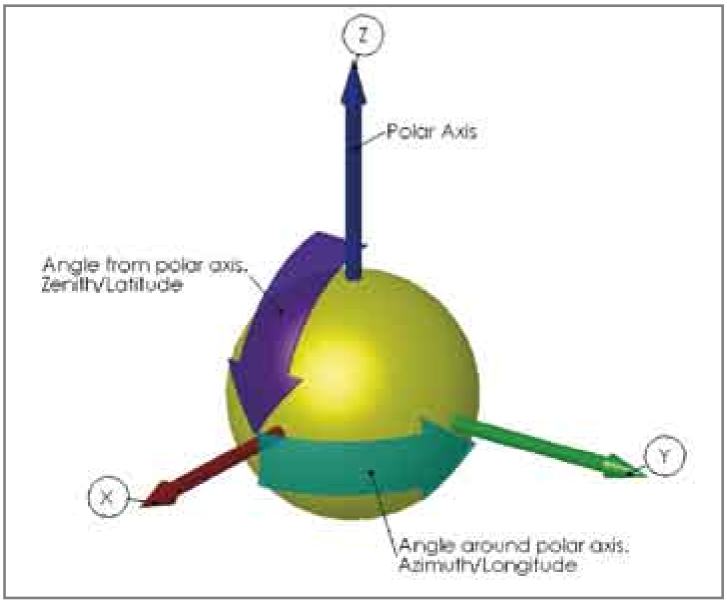

Figure 4: Spherical Coordinates.

When a specification is considered, (such as max allowed luminance outside of a given angular range), it is sometimes useful to assign a small number of discreet contour levels with the maximum magnitude being the limit for the first contour level. Then at the given zenith limit, the specification is easily observed by whether the first color level "bleeds across" the specification ring or not. For example, consider a specification that calls for less than 1000cd/m² outside of the 65° zenith angle. If the contour level from 0-1000cd/m² represents red, and >1000cd/m² is blue, on observing the plot, the spec is met as long as no red falls outside the region of the 65° zenith ring. This can be more informative than a polar plot which only takes several slices through the distribution, because the slices may "miss" a region where the specification is exceeded. This may not be an issue if the photometrics are strictly specified by the polar slices, but it is still useful to know if light is spilling out of the specified region.

A polar plot takes slices through a contour plot for constant azimuthal values. The polar axis on this plot then represents the zenith coordinate, and the radial axis is the photometric magnitude. Typically multiple slices are taken (for instance at 22.5 degree increments) with each slice overlaying the plot as a different color. An example is shown in Figure 5.

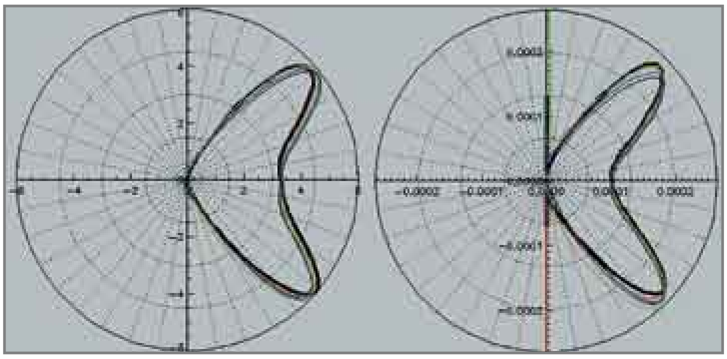

Figure 5: Polar Plots. Left: Luminous Intensity Right: Luminance.

The data from a polar plot can be equivalently plotted on rectangular axes. The x-axis is the zenith angle and the y-axis is the photometric magnitude. Again multiple slices can be overlaid with different colors as shown in Figure 6.

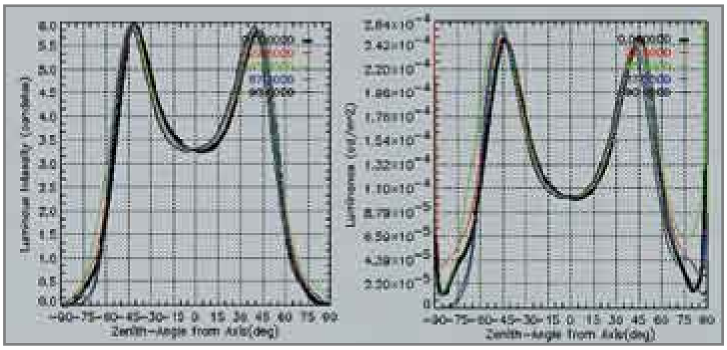

Figure 6: Rectangular Plots. Left: Luminous Intensity Right: Luminance.

The Söllner plot is another rectangular plot that is common for specifying office lighting. Its y-axis is instead the zenith angle and the x-axis is a logarithmic scale of the photometric magnitude. The angular range is typically truncated to the region of interest (instead of 0°-90° for example 45°-90°). This plot lends itself to quickly checking whether a maximum specified photometric magnitude is exceeded within a given angular range. See Figure 7.

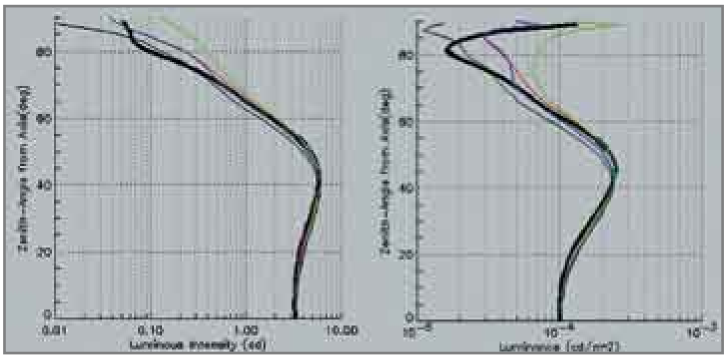

Figure 7: Semi-Logarithmic Plots. Left: Luminous Intensity. Right: Söllner plot for Luminance.

Finally, often the light distribution at a given plane is desired. This can be observed by setting a detector at the selected location and then collecting and plotting the flux per unit area there. This is an illuminance map (see Figure 8).

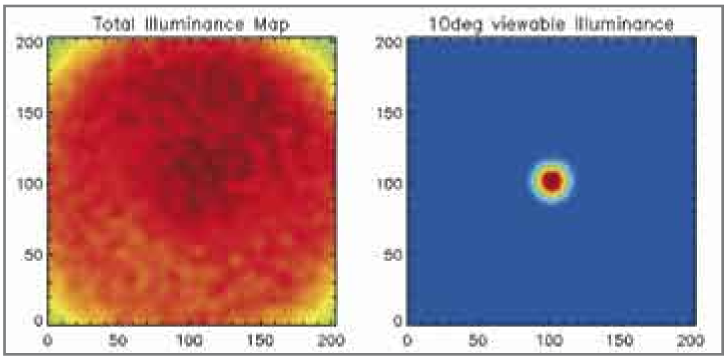

Figure 8: Illuminance maps. Left: Total flux per unit area at a collection plane. Right: Same distribution with rays outside 10° excluded from the flux contribution; this is an approximation to what the eye might perceive.

A way to roughly simulate what the eye would perceive is to suppress the flux contribution of all rays that exceed a 10° observable cone. This is an approximation because the area of the flux distribution will usually be greater than the eye's iris aperture. Furthermore, the foveal cone of the eye does not subtend an angle that large. It is typically necessary to consider at least a 10° cone however because reducing the angle, for example to 2°, greatly reduces the amount of rays in the flux distribution and produces a noisy illuminance map. Ideally however, visual simulation is achieved through a photorealistic renderer; see for example: Radiance[2] (which powers Adeline [3]), POV-Ray [4], Photopia [5] and Lightscape [6]. This topic is too vast to examine here, but it should be recognized that many rendering software packages exist and one needs to select a package that is sophisticated enough to import a source file representing the LED distribution.

Specifications

After generating the photometric analysis for a given design, the next task is to compare it to the requisite specification. Common lighting specifications include RP-1 [7] (for office lighting) and ITE [8] (for traffic signals).

The recommended preferred and maximum average luminances for office lighting are excerpted from Table 7-1 of Reference 7 and given below in Table 1. For comparing photometric data to RP-1, it is useful to overlay the specification boundaries on a Söllner plot of the data. To satisfy the specification, the data should not exceed the luminance boundary at the given angle (see Figure 9).

Degrees from vertical	Preferred maximum luminance	Maximum average luminance
55°	850 cd/m²	none specified
65°	350 cd/m²	850 cd/m²
75°	175 cd/m²	350 cd/m²
≥85°	175 cd/m²	175 cd/m²

Table 1: RP-1 specification.

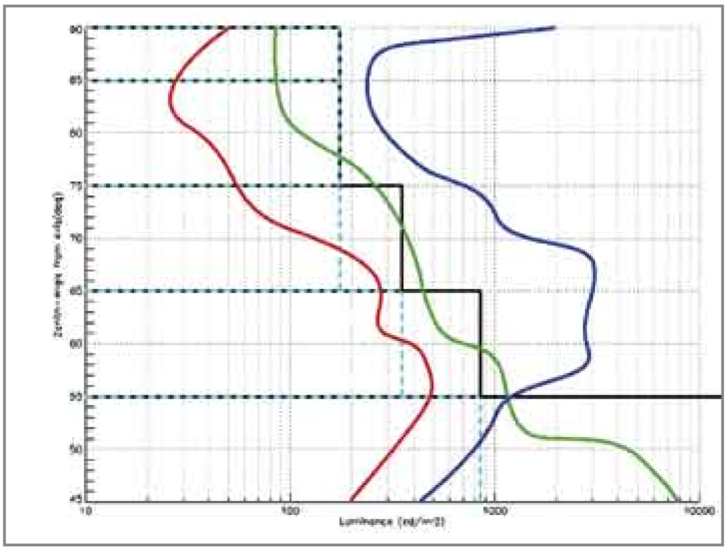

Figure 9: Example Söllner plot including RP-1 specifications. The dashed cyan lines outline the preferred maximum average luminance values and the solid black lines outline the absolute maximum average luminance values. The sample data sets are: Red: within the preferred range, Green: exceeds the preferred range, but still within the absolute allowed range, Blue: out of spec.

The maintained minimum Luminous Intensity for LED traffic signals are excerpted from Table 1, section 4 of Reference 8 and reproduced in Table 2. To better grasp the numbers, a contour distribution can be created by bilinearly interpolating the table values into a large polar array. This is demonstrated for the red signal in Figure 10.

Vertical Angle Down	Horiz. Angle Left & Right	8-inch Signal			12-inch Signal		
		Red	Yellow	Green	Red	Yellow	Green
	2.5	133	617	267	339	1571	678
	7.5	97	449	194	251	1159	501
	12.5	57	262	113	141	655	283
2.5	17.5	25	112	48	77	355	154
	2.5	101	468	202	226	1047	452
	7.5	89	411	178	202	935	404
	12.5	65	299	129	145	673	291
	17.5	41	187	81	89	411	178
	22.5	18	84	37	38	178	77
7.5	27.5	10	47	20	16	75	32
	2.5	37	168	73	50	234	101
	7.5	32	150	65	48	224	97
	12.5	28	131	57	44	206	89
	17.5	20	94	41	34	159	69
	22.5	12	56	25	22	103	44
12.5	27.5	9	37	16	16	75	32
	2.5	16	75	32	22	103	44
	7.5	14	65	28	22	103	44
	12.5	10	47	20	22	103	44
	17.5	9	37	16	22	103	44
	22.5	6	28	12	20	94	41
17.5	27.5	4	19	9	16	75	32

Table 2: ITE specification [8] for minimum Luminous Intensity values for LED traffic signals.

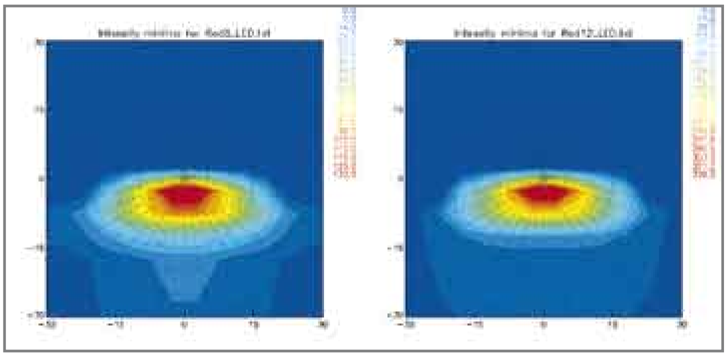

Figure 10: Bilinearly interpolated contour plots for the minimum luminous intensity distribution for red LED traffic signals according to the ITE specification8. The zenith increment scale (i.e. the grid formed by the circles) is 5°. Note that the contour peak values are different although both plots are scaled to the same colormap. Left: 8" signal. Right: 12" signal.

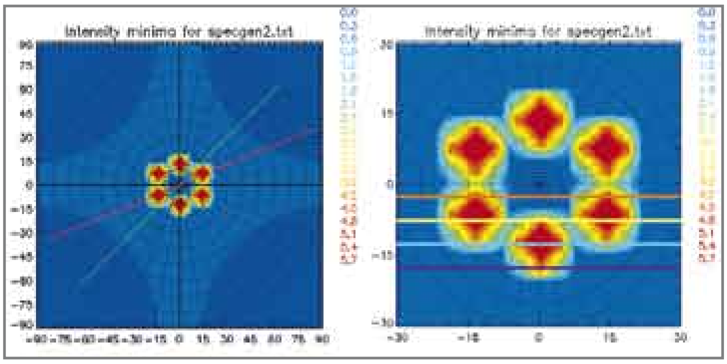

Figure 11: Arbitrary distribution for sample specification. Left: Zenith increment scale is 10°; also shown are the polar slices: Red:22.5°, Green:45°, Blue:67.5°. Right: Zenith increment scale is 5°; also shown are the horizontal slices at the following declination angles: Orange:2.5°, Yellow:7.5°, Green:12.5°, Purple:17.5°.

For the purpose of a sample analysis an arbitrary specification is created. This distribution has a minimum peak intensity of 6.0candelas at six distinct propagation directions as shown in Figure 11. The specification shall require that the minimum luminous intensity exceed that of the distribution everywhere along the following polar slices: 22.5°, 45°, 67.5° and 90° (similar to an office lighting specification). In addition, it should exceed the distribution at every horizontal angle at the following declinations: 2.5°, 7.5°, 12.5° and 17.5° (similar to a traffic signal spec.).

To compare the distributions, one can just look at the luminous intensities of the design and the specification side by side. But since the actual specification is called out in terms of polar and rectangular slices through the photometric distribution, it is most informative to instead slice both the data array and the specification distribution and then overlay the resulting plot lines on the same chart. The polar slice data comparison for the sample Luxeon LED is shown in the top row of Figure 12 and the rectangular slices in the bottom row. It is apparent that the specifications are not met. Auxiliary optics can be designed to shape the distribution to meet the specification. The design for an optical element to accomplish this will be consider in Section Design

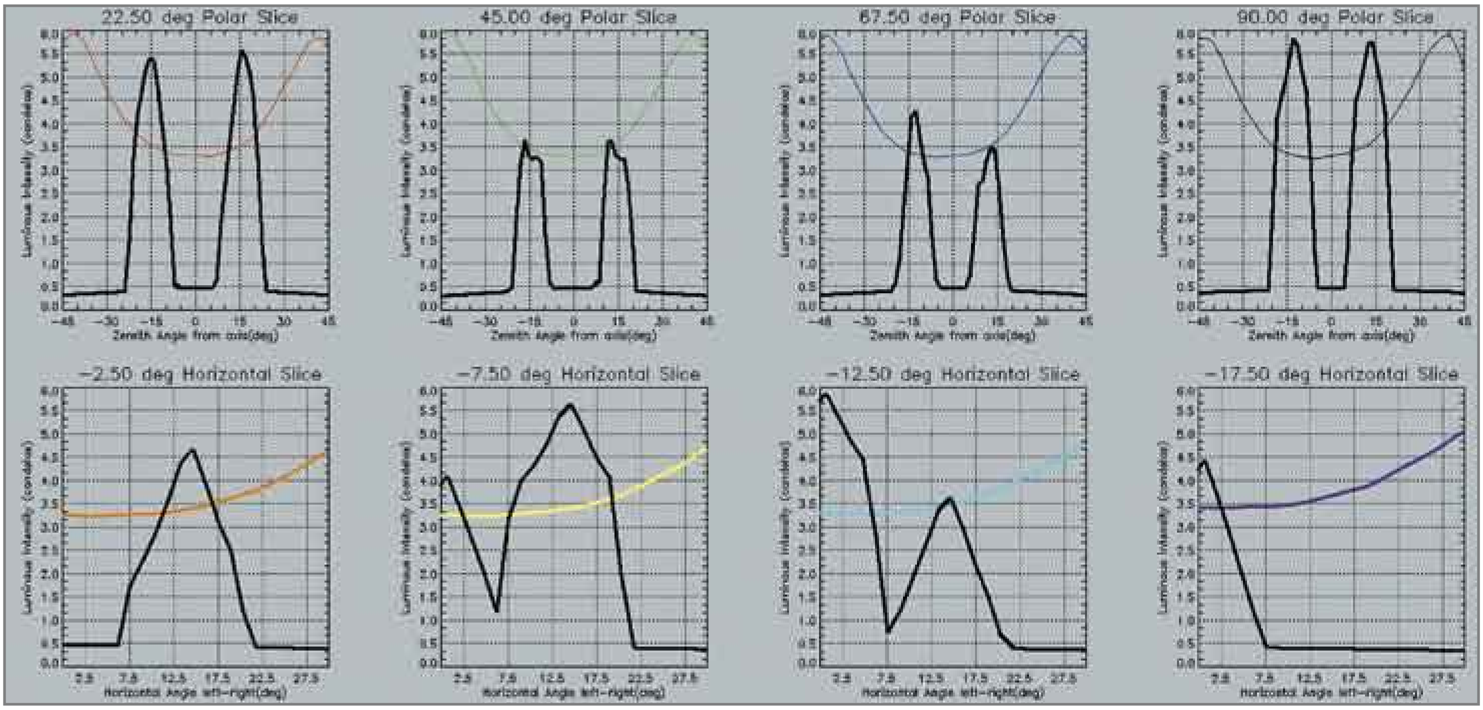

Figure 12: Top Row: Polar slices through the four specified azimuth angles. The black line in each graph represents the minimum intensity requirement (each is the result of taking a data slice though the specified angle of the specification distribution). The colored lines are plots of the data through the output distribution. Since the colored lines dip below the peaks of the black lines, the specification is not satisfied. Bottom Row: Rectangular/ horizontal slices at the four declination angles. As before, the black lines are the minimum required and the colored lines are the output results. Again, the specification is not satisfied.

Applications

Frontlighting and backlighting

Enormously popular applications of microstructured optics are in backlights and frontlights (see Figure 13). These are flat panel type waveguides used in LCD monitors, cell phones, pagers, PDAs, handheld games and other displays. Especially when using LEDs, fine photometric control of the light distribution is necessary in order to present the observer with a uniform observation field. This is usually accomplished with some form of waveguide preconditioning or integrating optic. This optic serves to illuminate the edge of the flat panel waveguide with a uniform input. Once inside this waveguide, microstructure is heavily relied upon. By either printed or etched dots or rows or patches of prisms, the light is selectively transferred out of the waveguide so that the whole panel appears uniformly illuminated. Still afterwards, more microstructure is important in providing the observer with the requisite screen brightness. Often a prism film is used to increase the gain and efficiency while recycling light that would otherwise be wasted.

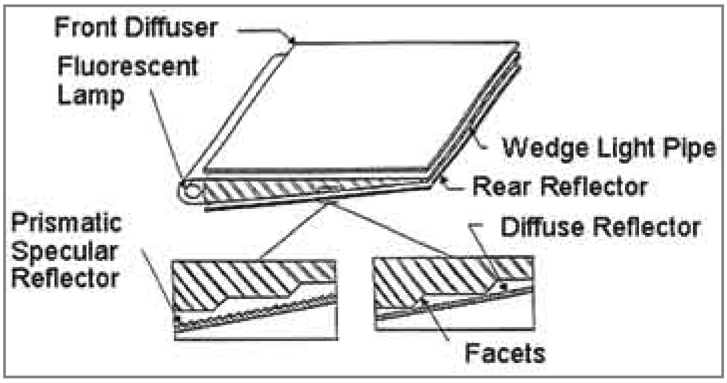

Figure 13: Schematic of a typical backlight. In an LED application, the fluorescent lamp would be replaced with multiple LEDs and an integrator optic.

Traffic and rail signaling

A popular national trend is to replace incandescent traffic control signals with LED signals. There is a well defined standard for the luminous intensity performance of these signals (see ITE specification in Table 2 and Figure 10). Accordingly, any light that is directed upwards is a waste of power and can be redirected with the help of microstructured optics. Additionally, new designs with microstructured optics eliminate the unpleasant "discreetness" of large LED arrays by using higher intensity modules in a rear projection fashion (a example is shown in Figure 14). Custom lens elements implementing microstructured optics are ideal for redirecting these sources to a pleasantly uniform ITE specification.

A similar application is in the Rail signal industry. Rail signals are different from traffic signals in that they are mostly viewed in-plane (instead of significantly declined from the optical axis). They also have the unique requirement of being visible from far away and all throughout the subtended range a train operator perceives while traveling past the signal. Additionally, it is undesirable for train operators on the opposite side of the sign to have visibility of the light (light directed in this region is also wasted energy). Consequently a well engineered "side lobe" is required. The use of microstructured lenses and prism arrays makes all this possible.

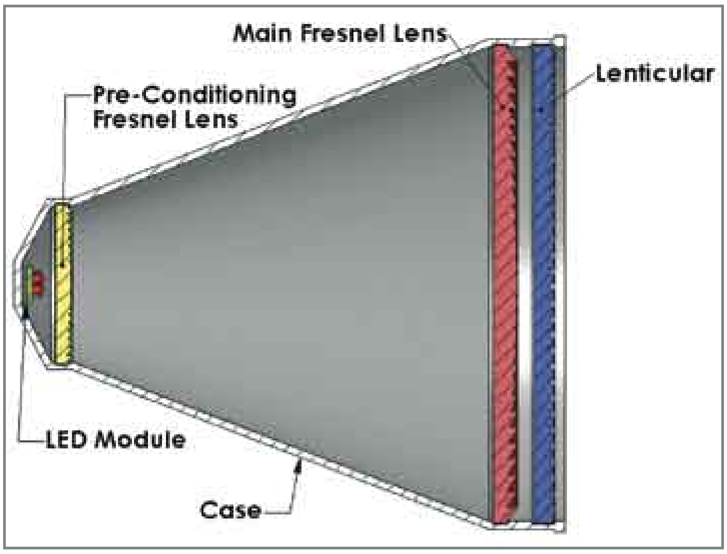

Figure 14: A traffic signal sample design that uses a high intensity LED module in rear-projection fashion.

Flashlights

In an LED flashlight application, multiple LEDs may be used as the light source. This array is larger than a single typical flashlight bulb and for that reason it may be too unwieldy to create an effective reflector. Light collection and collimation can be improved by using a Fresnel lens on the output of the flashlight instead.

Office lighting

Although the author currently does not know of any office lighting fixture yet that implements LEDs, it is probably not unreasonable given the current state of the technology to design an RP-1 compliant direct/indirect fluorescent/LED hybrid. The downlight requirements for direct/indirect illumination are not extreme so using optically conditioned high intensity LEDs is plausible. At the same time, all uplight contributions can be provided by the fluorescent (instead of splitting it between uplight and downlight) so a fixture that normally uses two fluorescents may potentially be replaced by a fixture that uses a single fluorescent in combination with LEDs. The color rendering of such a hybrid however may be unusual.

Video Projection

Potential for microstructured optics may yet exist in video projection with the advent of newer LEDs. Traditionally plastic optics cannot be applied as source conditioners (i.e. field lenses and lens arrays) because the close proximity of the plastic to the extremely high temperatures of the incandescent source damages the optics. It would be highly desirable to use plastic optics in this application over glass because of plastic's lightweight. Should LED brightness become sufficient for video projector applications, their inherent high efficiency and low thermal output (when compared to a comparable incandescent source) could make the use of plastic optics for lamp conditioning much more reasonable.

Additionally, there is the option of molding in a Moth-eye structure [9] for improved efficiency. Aside from the incremental tooling cost, process cycle time and manufacturing unit cost are marginally increased compared to a similar part without Moth-eye. In comparison to thin film coatings, the performance and value is enhanced considerably [10].

Miscellaneous

Of course the potential applications for LEDs are innumerable. For any of those applications where fine photometric control is required, or simply a different distribution from the manufacturer supplied LED is preferred, microstructured optics may be used in conjunction. More examples would include sign illumination in which optics can more evenly distribute the bright LED spots over the face of the sign, artistic lighting in hallways, movie theatres and galleries, marker lighting for roads and runways in which a cylindrical upward inclined distribution is desired, machine vision, automatic teller bank machines, pedestrian signs, automotive interiors such as for the instrument panels and for the dome lights, automotive exteriors such as for the brake and signal lights, street lighting, ring lights etc.

Design

A concise description of Illumination System design is given in Reference 11. To summarize, the process involves: building the fixed geometry, accurately modeling the source, determining the requirements, evaluating simple initial concepts, optimizing a selected concept, verifying the performance given geometric deviations, tolerancing, prototyping and finally testing [11]. The sample design presented in this section loosely follows these tenants. No geometric deviation or tolerancing is performed however and as of this writing the photometrics for the sample design presented have not yet been verified by testing.

Optical modeling tools

There are numerous ways to create a model of an optical layout. Tools of the trade commonly consist of a mechanical CAD package, a sequential raytrace package with global optimization, a non-sequential raytrace package and radiometry ray generation software.

One of the most straightforward ways of setting up a layout for raytracing is to draw the setup in a mechanical CAD package (SolidWorks [12], ProEngineer [13], Rhinoceros [14], AutoCAD [15] to name just several). Once completed most CAD programs can export to a format that can be imported by most raytrace packages. This methodology can be tedious for design optimization because each decided change in geometry requires redrawing the system, re-exporting it from the CAD package and re-importing it to the raytrace software. The process can be streamlined somewhat by using parametric software such as SolidWorks or ProEngineer. Parametric CAD software defines its geometry according to variable constraints. By judiciously constraining the model, the entire geometry can be quickly regenerated just by changing the value of a variable.

Sequential raytrace packages excel at quickly raytracing and optimizing an optical layout. The great speed of the software comes from the assumption that light will always travel to incidence on the next optical surface defined in the database. This is perfectly acceptable for imaging systems. Also adding to the power of most sequential raytrace software is the inclusion of global optimization algorithms in the software. By defining a figure of merit (such as spot size) and some system variables (such as radii of curvature), the global optimization routines can modify the system automatically until optimum performance is achieved. Popular software in this category is OSLO [16], Zemax [17] and CodeV [18].

For nonimaging systems and for stray light analysis of imaging systems, where light does not necessarily travel sequentially, a non-sequential raytrace package is required. In a non-sequential raytrace, light is permitted to reverse direction and become incident on optics it has already traversed, it can get trapped between surfaces, or it can skip the next optic in sequence altogether. Because of this generality, non-sequential raytracers trace rays much slower. This tends to make automatic global optimization more difficult to implement. Popular software in this category is ASAP [19], TracePro [16] and LightTools [18]. ASAP has a linear optimizer built in which can be readily applied in the design process. TracePro and LightTools have none, but the underlying macro languages are substantial enough to write one from scratch.

In order for a raytrace simulation to be as close to reality as possible, it is best to have the actual source photometrically characterized. This can be done by accurately measuring the source in a photometric lab. A typical photometric report will include the photometrically accurate far field luminous intensity values. From this data, careful calculation can result in the definition of a source model that is approximately apodized in accordance with the real source. It is most convenient however to use a software package such as ProSource [20] coupled with photometric measurements supplied by Radiant Imaging [20]. This allows the designer to generate accurate ray distributions via a nice user interface.

Other useful software includes scientific data visualization software (IDL [21], PV-Wave [22], Origin [23]) and capable programming languages (C/C++, Perl, Fortran and many others). Data visualization is an important tool in combination with raytrace packages because the data analysis portions of raytrace software are comparatively limited for purposes of calculation and publication. Programming language functionality adds similar capability, and also can be used to augment the raytracing software functionality.

Choosing an LED

Often, a customer seeking a tailored photometric output will already have an LED specified. It is most convenient for the designer if the LED is common enough to have been characterized and published in the Radiant Imaging Source database [20]. Any and all photometric data that can be supplied is useful in the design. It is also appreciated when a supplier of LEDs has gone through the effort of characterizing their LED sources and provide the data as requested.

If the design engineer has the liberty to choose an LED from the start, a significant factor in choosing a supplier is the free availability of characterization data (for example, downloadable photometric characteristics and published mechanical CAD drawings). This reduces the initial steps of acquiring varied samples of LED's for measuring their characteristics. With photometric data readily available, a design feasibility study, (and indeed a full design) can be completed without having to receive a physical sample.

LED source modeling

Before considering how to shape the design photometrics with optics, it is paramount that an excellent source representation be used. Approximations and inaccuracies will at best transfer linearly through the system effecting error in the results. More likely though, errors will be compounded through the ray propagation yielding extra unrealistic results and incorrect flux magnitudes. (Concerning source modeling, see for example, References: 24, 25, 26 and 27.).

The LED source model can be simulated either by geometric detail or by ray generation based on accurate photometric measurements of the LED [24, 27]. Raytraces based on a characterized source model generally produce photometrics that are more accurate than a strictly geometric source model. However, if the source is to be used in a system where light may be recycled and impinge back on itself, it is essential to have its geometry included. The following merges the CAD geometry for a Luxeon 1-Watt white LED (LXHL-MW1A) [1] with the Radiant Imaging generated rayfile for this LED.

Figure 15 shows several views of the CAD geometry for the LED with the rayspots overlaid. The origin for both the CAD and the ray representations are coincident and is located at the center where the glass envelope meets the base. ProSource creates rays at arbitrary starting positions. As shown in Figure 15 all of the rayspots originate inside the boundary definitions of the LED. If the LED geometry is to be included in the raytrace, this is not where the initial ray coordinates belong. ProSource generates the rays from the perspective of an observation plane after the rays have already left the LED. Putting the rays back behind the glass dome and propagating them through again is not correct. To get the rays "out" then, they should be free-space propagated to an exterior dummy surface. This is accomplished with an absorbing shell located to surround the transmissive portion of the LED (Figure 16). The LED geometry is removed, and the rays are inserted (Figure 17).

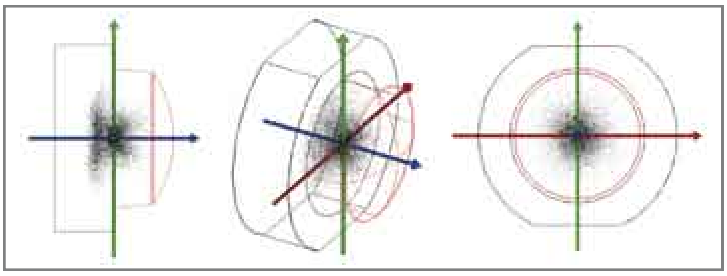

Figure 15: Views of the LED with the originating source rays overlaid. The red dome feature is the glass envelope and the black clipped cylindrical feature is the opaque base.

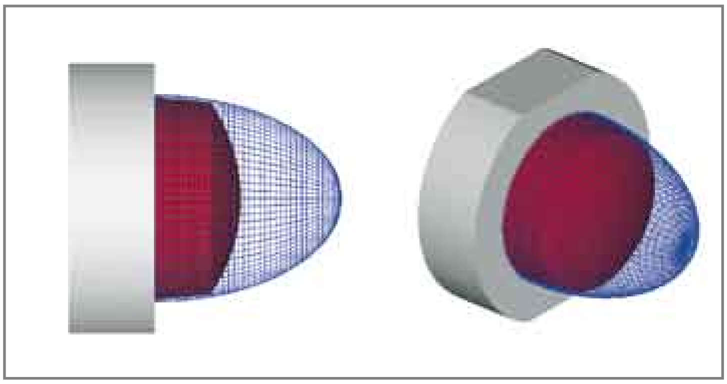

Figure 16: LED with absorbing shell (blue) just surrounding the transmissive dome (red).

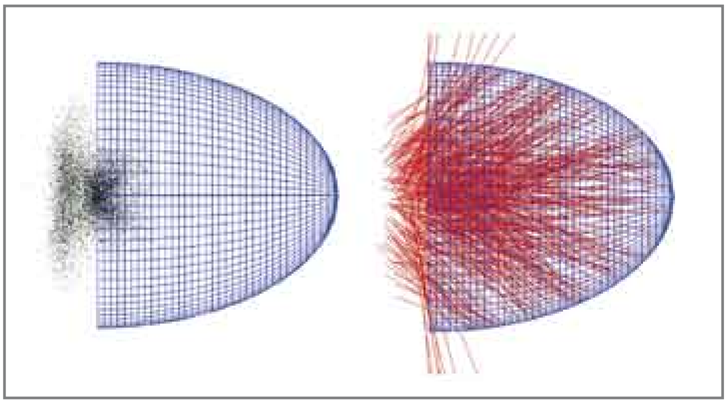

Figure 17: Left: Absorbing shell for collecting rays outside of the LED. The spot cloud shown is the original ball of rays that would lie inside the LED geometry. The LED geometry has been removed so these rays can be free-space propagated to the collection shell. Right: Absorbing shell with traced rays. Rays that miss the shell are presumed to be from stray light and are dropped.

Next the rays are propagated (through free space) to be absorbed at the shell as shown in Figure 17. Note that some spurious rays are not coincident on the shell. In reality, this is not plausible because all emitted light should only come through the transmissive window of the LED. Most likely this is caused by ProSource reconstructing ambient scattered light. These rays are a small fraction of the total flux (less than 0.5%) and are deliberately dropped and ignored in further raytraces. The rays that are captured at the shell are transferred to a new rayfile to be used for all future raytraces. The CAD geometry for the LED is added back in and the location of the rays are plotted in Figure 18.

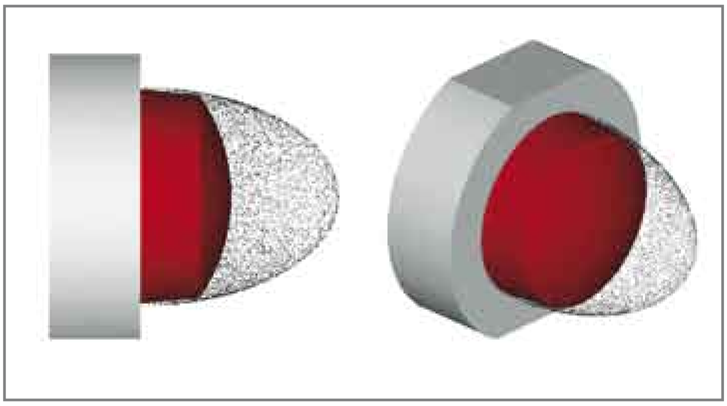

Figure 18: LED with externally captured rays. The absorbing shell is removed and the new ray positions are saved for future raytraces.

Reflector design

The science of designing a reflector to maximally concentrate light from a source emitter is well researched (many useful publications are compiled in Reference 28). One type of reflector which can maximally redirect light output from an input plane is called a Compound Parabolic Concentrator or CPC [29, 30, 31, 32].

A schematic of a CPC is shown in Figure 19. As per the variables defined in that Figure, the following are some useful formulae for CPC design [29, 30]:

$$d_1 = d_2 \sin(\theta_{max})$$

$$L = \frac{d_1 + d_2}{2\tan(\theta_{max})}$$

By choosing a smaller value for θmax, a higher degree of collimation is achieved. However, this also very quickly increases the requisite length (L) of the CPC. This can be traded off with not extending the CPC length out to L. Hinterberger [29] notes that truncating the reflector at 2/3L does not decrease the aperture diameter very much. Although, in his application, the CPC is used to collect light onto the focal plane (instead of collimating a source placed at the focal plane). When truncating the CPC length for source collimation, careful attention should be paid to its effect on the output half-angle.

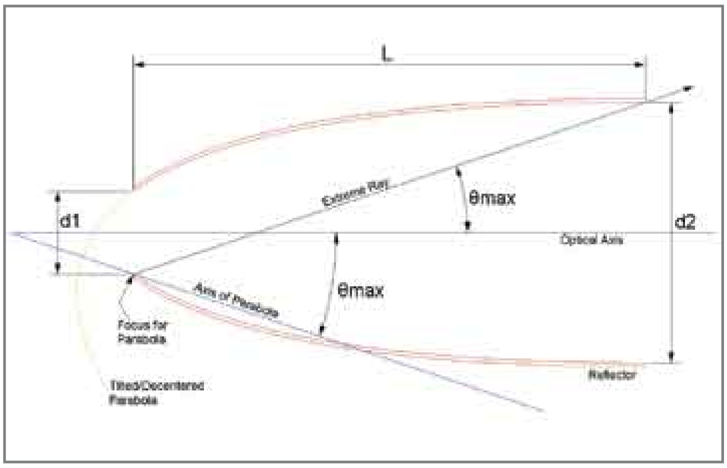

Figure 19: A Compound Parabolic Concentrator (CPC). Variables: d: Source plane diameter; d2: Exit aperture diameter; L: CPC length; θmax: Output half-angle.

It can be shown that if a CPC reflector is converted into a solid dielectric with an index of refraction n satisfying: 2 ≥ n ≥ √2 (a range of indices covered by common materials) then total internal reflection is supported at the CPC walls. This method can have significant cost benefit by eliminating the need to add a reflective coat. Furthermore, an engineered microstructured surface can be incorporated into the output surface for additional photometric control. In this way, both the light collector and a refractive control structure can be formed by a single injection mold.

At least one company capable of supplying CPC reflectors on a custom manufactured basis is Opti-Forms [33].

Refractive microstructure design

- **Layout**

The approach taken for designing a refractive microstructure is highly dependant on the application. For designing and manufacturing components in a well developed field, the design can practically be automated and therefore completed at little to no cost. An example is the design of a collimating Fresnel Lens. Since generalized software has been written to create facet geometry according to a lens prescription, the lens design is practically a commodity. The most significant costs are for tooling and manufacturing.

A stringently specified project will be much more complex. As an example, take the arbitrary specification fabricated in Section Specifications, Figure 11. Accordingly, the intent of this section shall be to take the on axis output from the LXHL-MW1A seated in the CPC and create six radiating off axis spokes. To begin, it is necessary to choose an optical structure of approximate proper form. This will give the optimization process its necessary starting point. In this case we will select a six-sided pyramidal structure; each facet of the pyramid will direct light toward one of the spoke directions [34].

Early in the design process, it is substantially important to consider tooling and manufacturing. Given the unlimited design flexibility within the scope of design software, it is easy to create a design that cannot be tooled or is prohibitively expensive to manufacture. It is frustrating to put significant effort in developing an optimal design to only later find out that it cannot be made. Sometimes it is possible to alter the design to make the part realizable, but it will inevitably be at the cost of performance. Usually it is best to include tooling and manufacturing constraints within the optimization process.

Depending on the tooling process used, different constraints may exist. In this case, the tooling is made by diamond ruling. We can form a six sided pyramidal structure by engraving crosscuts inclined to each other by 60° (see Figure 20). This will not create standalone pyramids; sub-prism features will also be formed. Understanding these features and including them in the design process is essential. To accomplish this, it is useful to make a three-dimensional representation of the solid geometry in CAD software (see Figure 20).

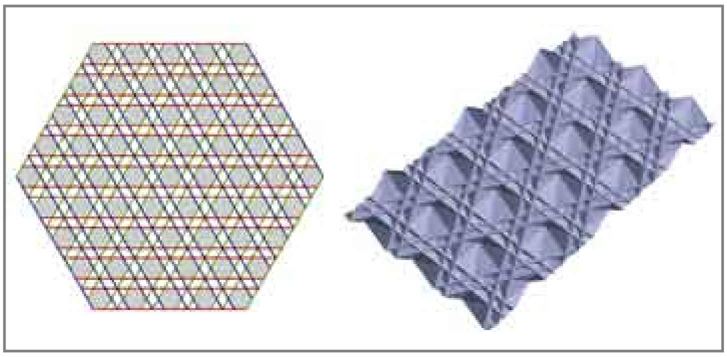

Figure 20: Left: The tool is engraved at three separate cut directions (red, green and blue) to form a repeating 6-sided prism structure (shaded regions). Right: The solid geometry formed by ruling the pattern shown at the left.

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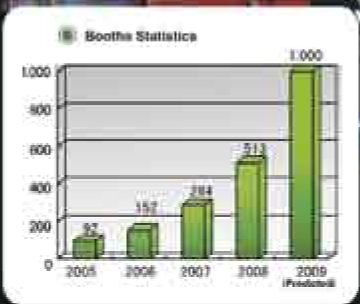

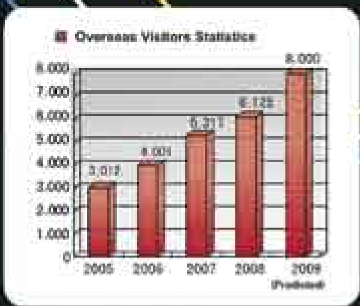

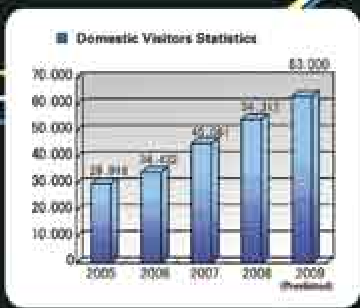

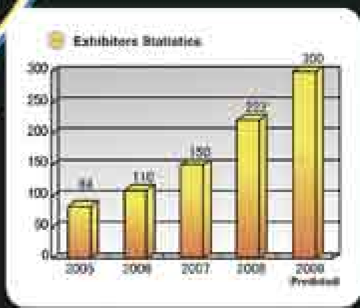

Concurrent Activities

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On considering pitch, it is usually not so important to design the microstructure to the exact dimensions of the finished product. When the far field luminous intensity distribution is the specification of concern, often 10 prisms will do almost as good a job as 1000. The requirements are that the facet angles be maintained and the ratio of geometry feature dimensions remain fixed. The size of the microprisms can usually be chosen to satisfy the aesthetic requirements (whether the features should be visible to the unaided eye or not). Also tooling may be considered in selecting the pitch. Larger feature sizes decrease the time it takes to make the tooling master. Especially fine structure can approach the limit of tooling capability in addition to degrading performance as the ratio of feature size to tooling error (burrs, radiused edges etc.) decreases.

Furthermore, it is beneficial to exploit large facet size in the computer model itself. Generating numerous quantities of prisms in the model requires the computer simulation to solve a plethora of ray-boundary intersections. This is time consuming even on the currently fastest available computer hardware. Design iterations can proceed much more efficiently if larger size prisms are considered. An additional trick which can reduce the number of prisms stored in the raytrace database is to generate only several rows of prisms and then to bound them on either side by perfectly reflecting mirror planes. It is important that the planes be located such that symmetry of the facet structure is preserved (that is, in unfolding the prisms about the mirror planes, the microstructure should appear uninterrupted). This technique is not always possible and it is inaccurate at the boundaries, but for design purposes, it saves a lot of time. After design is complete, or during the last few iterations, the pitch may be reduced to actual size and the full volume of prisms generated (removing the perfect mirror planes) to verify the photometrics. This may not always be possible however when particularly small prisms are applied over a very large area; such great numbers of geometric definitions may exceed the capabilities of the software or take eons to raytrace.

With some of the new features being implemented in raytrace software, the issue of pitch and number of prisms affecting raytrace time can become mute. If the prism structure is simple enough, the virtual microstructure ability of RepTile in TracePro [16] and 3D-Textures in LightTools [18] can apply vast numbers of prisms to a surface with the definition of a single facet period.

- **Optimization**

Once a the basic geometric form is developed, a process of optimization may commence. This can range anywhere from completely manual to nearly fully automated. In a manual optimization, each iteration would involve regenerating or reprogramming the facet geometry based on intuition and on how previous designs performed. With moderately stringent photometric specifications, and a solid grasp on how the optical facets interact with the light input, a manual optimization is completely reasonable and may be the quickest way to achieve a final design.

If after experimenting with a few manual optimization iterations, it becomes apparent that too many factors are interacting to seek a resolution by hand, then an automated optimizer should be applied. This is much more time consuming to set up initially, but it is far more efficient at characterizing large numbers of possible geometries then a manual process.

The first step in automated optimization is to define an error function (or figure of merit). The error function is some way of quantitatively defining how good the system performance is with a single number. As the error function approaches zero, the system performance improves. The design of an appropriate function can be complex. In this case, and in many other cases where just the luminous intensity distribution is of concern, it can be simple. The error function can be defined as the difference between the total flux of the LED and the amount of flux contained within the desired propagation spokes. If all flux was contained within the spokes, then the error function would be zero and an optimum design would be signified. In this example, there is no restriction on cutoff angle, but if a specification were to call for an explicit cutoff, an additional factor should be added to the error function to strongly punish the system merit until the cutoff requirement is satisfied.

The next step is to figure out what parameters of the system may be allowed to vary in order that an optimal geometry will be obtained. Typical parameters are facet slope angles, draft incline angles and pitch to height ratios. To follow, much geometric calculation must be done to fully define the geometry based on these parameters. Care must be taken to neither over-constrain nor under-constrain the geometric definitions. With each optimization loop, the geometric definitions will be referenced procedurally. The procedure call will only provide the designated parameter variables from which the entire geometric representation must be created. It is also useful to include some reality checking functionality to weight the algorithm against driving the system towards a physically unrealizable geometry.

Before hitting the "go" button, there will be a number of remaining details to wrap up depending on the application. Of course the underlying flow control of the optimization process must be implemented. Some software includes built-in optimization routines. For others, it may be necessary (or preferable) to write one from scratch (some of the common software available is briefly discussed in Section Optical modeling tools). Also, optimization time should be considered. A balance must be struck between accuracy and iteration time by deftly manipulating the following parameters:

- number of rays to trace
- ray splitting and/or ray scattering
- ray termination
- geometric sampling resolution
- feature periodicity (when not using virtual microstructure)

If all goes well, then a solution may be found. Keeping track of all the geometries and the results of their merit function is paramount when a large number of iterations are traversed since the terminating solution (or more likely, the current solution being analyzed when you hit the "cancel" button) may not be the best system. This may be accomplished with supplementary software or scripting programs designed to analyze the wealth of raytrace output files and compile the results into a convenient table. The table should include enough information to recreate the system. It is also convenient to sort the results in terms of the error function and to include other analytical numbers such as output flux, efficiency and so forth.

If an acceptable solution is not found, the optimization process starts over again. This can include anything from redefining the original geometry paradigm, to providing more (or less or different) degrees of freedom in the way the algorithm modifies the geometry or to simply altering the initial conditions of optimization.

Results

The photometric results are analyzed as described in Section Photometric plots (see Figure 21). These results are compared to the specification of Figure 11 as described in Section Specifications (see Figure 22). The photometric requirements exceed the specified minimum values at all angles and therefore satisfy the specification.

The predominant feature of generating six off axis "spokes" is achieved. As shown in Figure 21 however, there is an added on-axis lobe to the distribution. This lobe is not strictly forbidden by our specification. As such, it should not be a problem. Admittedly though, it is a source of inefficiency, robbing light from the specified lobes. Also, although the on axis lobe may not be prohibited in a customer's original specification, a dialog must be opened to communicate the feature and prevent surprise. Without having realized it before, the customer may find that some photometric quirks actually are unacceptable and should be added to the specification. Still, given time and cost constraints it must be decided if any such peculiar photometric incarnations are acceptable. This also needs to be balanced in conjunction with the realization that further complicated design may yield microstructure features that prohibitively increase the tooling cost.

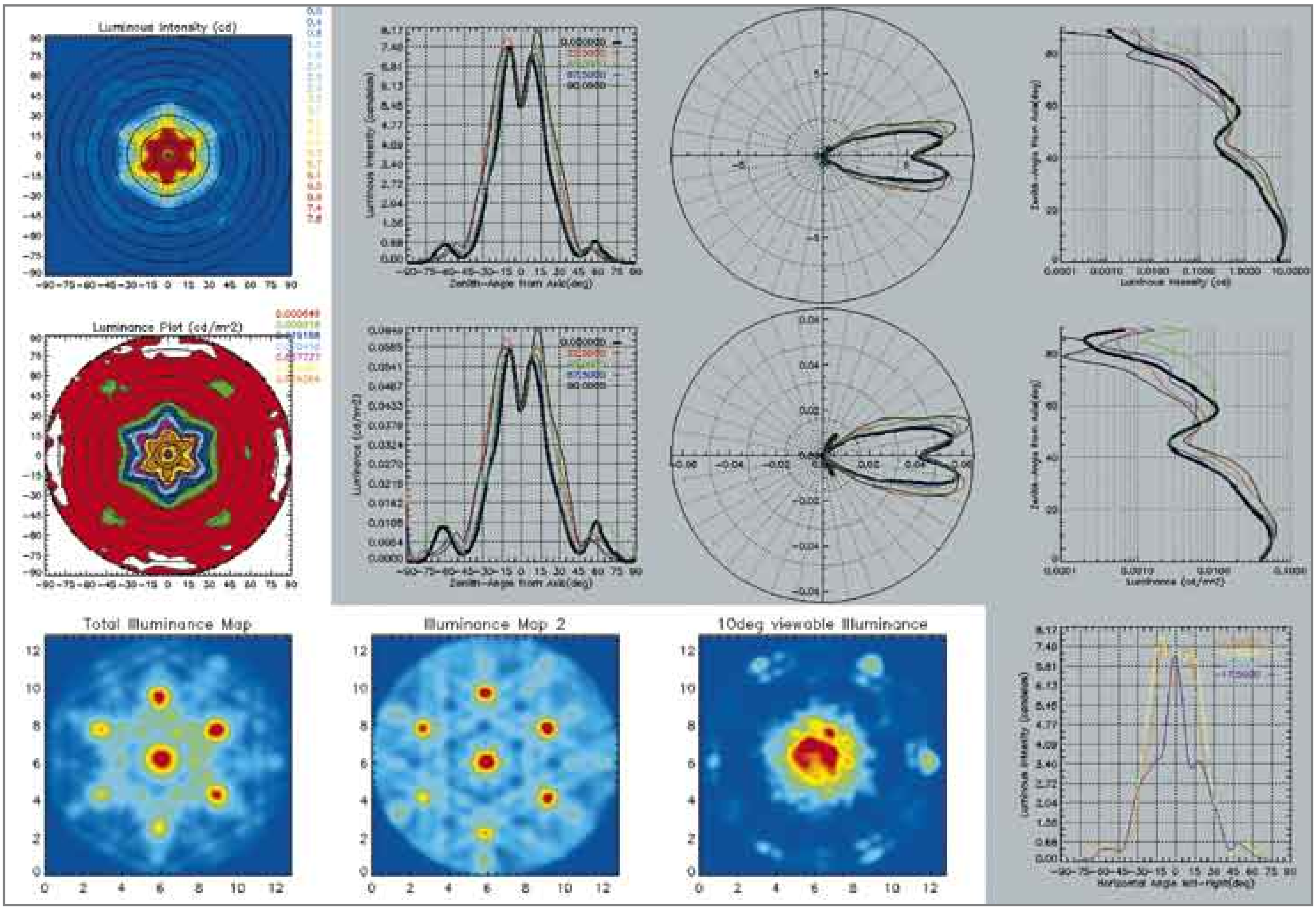

Figure 21: The various photometric plots for the output of the optimized sample design.

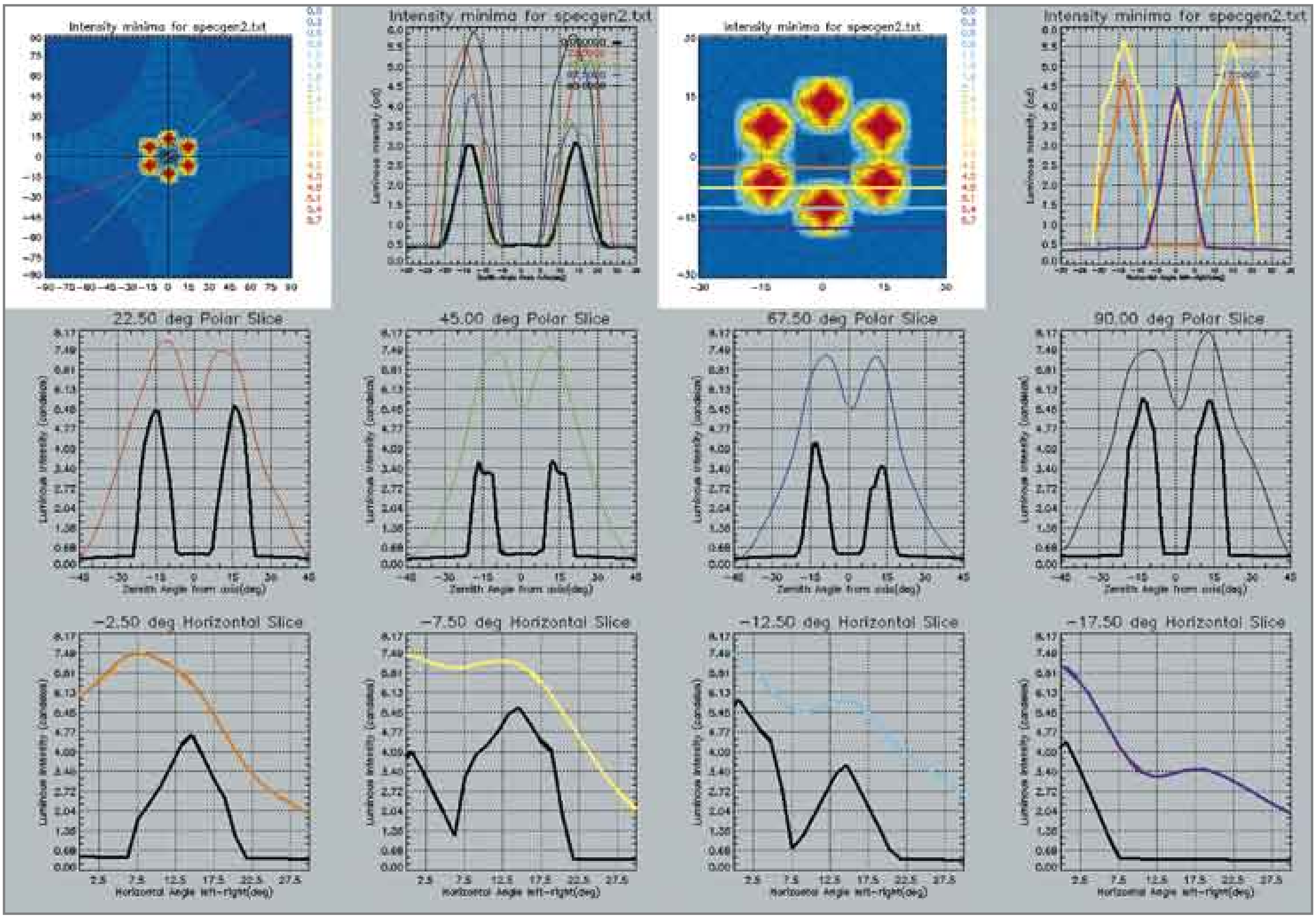

Figure 22: Comparison of the sample design photometrics to the defined specifications. The specifications are satisfied.

Discussion

LED vs. fluorescent

In designing microstructured optics for traditional lighting applications that use fluorescent sources, most of the methodology previously discussed for LEDs is directly applicable. A typical difference is the wide availability of photometric characterization for LEDs, which are highly accurate. Whereas such characterization files for fluorescent lamps are not freely published and are more expensive to generate. Thereby it is more common to use a less accurate geometrical model for fluorescent lamps. Furthermore, the emission cone of an LED is much more well confined then a cylindrical tube. This makes it easier to control the output distribution at a high efficiency since the LEDs can be spaced such that there is no or minimal overlap of the light distribution on the optic between neighboring sources. Conversely, this makes achieving a visual uniform field more difficult.

Source obscuration

The non-uniform illuminance pattern of the LED near field causes the significant complaint of source visibility. This generally occurs in applications where an LED is closely spaced to an optic. On the other side of this optic is the requirement for no source visibility with highly uniform illumination. This is a fairly tall order. Commonly, a high angle diffuser is used. A chief problem is that with said diffuser placed closely to an LED, its near field illuminance pattern is projected onto the diffuser and is consequently immediately visible and objectionable. A standard solution is to space the source as far away from the output optic as possible and use multiple diffusive layers maximally spaced. This is typically unwanted because it uses a large volume and is inefficient.

Under the constraints of small LED to lens distances, the solution to uniform output lies in light recycling. Injecting the LED source distribution into a tailored waveguide can be used to pre-condition the light into a uniform field. Waveguide extraction however can be an inefficient process. Some solutions to this problem are currently being investigated at Reflexite Display Optics with a strategic partnership for manufacturing technology that is much more highly efficient and can effectively obscure the source over a short distance.

Rigorous design vs. "plug and play"

The rigorous computer design method set forth is the recommend design paradigm, however, it is still quite popular to design with the "plug and play" approach. That is, buy some LEDs, maybe grab a lens, install it in the system, turn it on and see if it works. For loosely defined photometric requirements, indeed this might be the preferred design method because it is cheap and fast. If during the course of "plug and play" design one finds that trying multitudes of LEDs with random optics just is not working, a custom design would probably help. It may even be preferred to seek a customized design even when a plug and play solution is available; due to the precise photometric control that can be exercised with a microstructured optic, a photometric output may be sought that directs all light where it needs to go with very little stray energy outside of the requisite minima. This ensures maximal light utilization and promotes power conservation.

Inter-Compatibility

For any project in which an LED source is to be used, the designer should also take into concern obsolescence. As manufacturers refine their LEDs, it is not always a simple matter to unplug the old model and "drop in" a new one. For example, given that the trend is to increase brightness, for specifications that indicate a maximum luminance for a given cutoff angle, dropping in a brighter LED may exceed acceptable cutoff. Also, for a tightly toleranced layout in which the emission profile of the LED is precisely controlled, dropping in a new LED would be flawed if the new LED had a slightly different emission profile. For this reason, it is preferable that LED manufacturers carefully maintain LED emission profiles to be constant through LED generations.

At the discretion of the engineer based on the project requirements, system dependence to a specific LED can be minimized by loosening up the tolerances (usually at the expense of some system performance). Then when a new LED is installed it may be possible to bring it into specified performance by slightly adjusting the optic to LED distance. That is to say, adjustment of the emission profile may be tweaked by "focusing" the lens to different locations based on the LED. Allowing for such mechanical adjustments has the added benefit for optics that might be used simultaneously for several different color LEDs or several different manufacturer's LEDs (or both). Each unique LED may have a distinct "source to optic" distance. The final output profile for each optic however can be very similar. The alternative is to change the optical element surface structure per LED type. Each LED type would require its own redesigned optic and new molding tools would have to be made. Additional molding tools would have to be made later as newer generation LEDs replaced older ones.

When considering defocusing an optical element as a means of compensation over creating a new lens, it should be noted that one also needs to balance the added cost of altering the mechanics of a system to accommodate a different lens location. If expensive redesign is necessary to defocus an optical element, it may be more economical to make a new optic that functions in the existing system architecture.

Environmental conditions

Just as attention must be paid to the environmental conditions under which an LED will be subjected, so too should concern be paid for the microstructured optic. Typical materials are Acrylic, Polycarbonate or Polystyrene. Zeonor [35], Topas [36] and Arton [37] may also be used for very high temperature applications. The environmental conditions to consider are mechanical stress for durability, temperature for heat distortion, humidity for water absorption and ultraviolet light exposure for yellowing. Also material density may be important for weight considerations.

Manufacturing

Regarding manufacturing process, trade-offs, as usual, can be considered between cost and performance. The primary mechanisms in these trade offs for microstructured optics are fidelity, internal stress (which manifests as birefringence), precision and aspect ratio. A compression molding38 process has a long cycle time as compared to an injection molding process. The faster cycle times of an injection molding process can reduce unit manufacturing cost. This comes at the expense of prism fidelity, added birefringence and lower precision. Flow front freezing occurs in the plastic as the grooves are filled out and instead of sharp features being formed, a rounding out is caused (see Figure 23) [39]. As a result, the injection molded part is less efficient than the compression molded part. For a cost sensitive or high volume application in which efficiency, low birefringence and precision are not as important, this may be entirely acceptable. Of note, there are also hybrid processes known as Injection Compression Molding (coining) and High Precision Molding (HPM) [9] which enable cycle times close to that of injection molding while achieving fidelity, birefringence and precision close to that of compression molding.

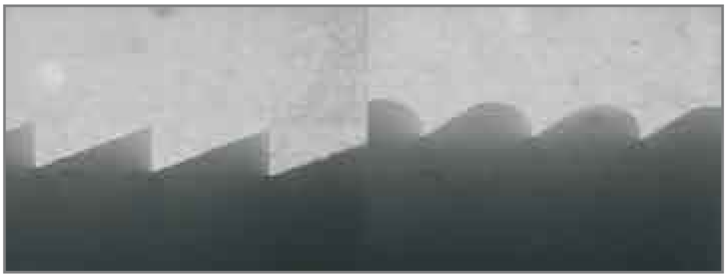

Figure 23: Side by side comparison of fidelity when molding microprism facets with: Left: compression molding and Right: injection molding.

Aesthetics

Aesthetic expectations for a microstructured optical design can sometimes cause trouble. Often a customer wants a certain look and "feel" to the finished product. This is not easily communicated through an input specification. Furthermore, it is not easily comprehensible throughout the design process to even tell what the visual impact of a finished product will be until prototypes have been made. Prototyping microstructured optics is a significant expenditure so it is best to get it right the first time. In many instances, the photometric performance of a particular design may well meet or exceed the photometric specifications, but if the aesthetic quality is not sufficiently pleasing to the customer then redesign or project termination will still occur.

Often, it is the presence of a glaring view of the source that is objectionable. Such a problem may not be obvious in a standard raytrace. The engineer is then charged with using intuition to scrutinize the geometric model and the raytrace to see if any glare paths are apparent. Ideally, aesthetics may be evaluated via very high end photorealistic rendering (this topic is touched on at the end of Section Photometric plots) before going to prototype. Otherwise some form of approximation must be used. For example, instead of tooling and molding the part, a cheaper prototype can be made by machining the microstructure directly into plastic.

Summary

A wide range of topics have been touched on through this discourse; each fully deserving of its own treatise. The applications for LEDs and microstructures in their own rites are vast. The combination of the two is a logical symbiosis.

The way in which performance is evaluated varies from industry to industry. Some of the standard ways in office lighting and signage were presented and are broadly useful over a great many applications. The specifics of evaluation however has to be determined on a case by case basis.

The design approach presented within was followed for a contrived example. The procedure for any other real world application will naturally be different, but the underlying principles are valid for most situations.

Finally there is a wealth of topics worth pondering when considering merging LEDs with microstructured optics. Some of the issues discussed were: LEDs versus fluorescent sources, source obscuration, rigorous design vs. "plug and play", inter-compatibility of different LEDs for a given design, environmental conditions, manufacturing trade-offs for cost with performance and finally aesthetic expectations. ■

Acknowledgements:

Thanks to Dave Jenkins and Doug Kreysar of Radiant Imaging20 for explaining concepts regarding how ProSource software generates rays. Thanks also to Michael Foley, Bryan Parks, Joe Lupone and Donna Desmarais for input regarding content and corrections.

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3 Adeline, Fraunhofer-Institut für Bauphysik, http://www.ibp.fhg.de/wt/adeline/
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Review of SMS Design Methods and Real World Applications

> Oliver Dross et al., Light Prescriptions Innovators LLC

The Simultaneous Multiple Surfaces design method (SMS), proprietary technology of Light Prescription Innovators (LPI), was developed in the early 1990's as a two dimensional method. The first embodiments had either linear or rotational symmetry and found applications in photovoltaic concentrators, illumination optics and optical communications. SMS designed devices perform close to the thermodynamic limit and are compact and simple; features that are especially beneficial in applications with today's high brightness LEDs. The method was extended to 3D "free form" geometries in 1999 that perfectly couple two incoming with two outgoing wavefronts. SMS 3D controls the light emitted by an extended light source much better than single free form surface designs, while reaching very high efficiencies. This has enabled the SMS method to be applied to automotive head lamps, one of the toughest lighting tasks in any application, where high efficiency and small size are required. This article will briefly review the characteristics of both the 2D and 3D methods and will present novel optical solutions that have been developed and manufactured to meet real world problems. These include various ultra compact LED collimators, solar concentrators and highly efficient LED low and high beam headlamp designs.

Keywords: SMS Design, Freeform Optics, Illumination, LED collimator, RXI, Nonimaging Optics, TIR-R, Diamond Turning, SMS Imaging, Condenser

Introduction

The SMS design method gives access to solutions of optical problems that can be formulated as the coupling of incoming and outgoing wavefronts. The number of wavefronts that can be controlled on both the input and output side, depends on the number of surfaces to be designed. Other methods create only one profile or surface at a time and therefore only couple one wavefront to another. This can be understood as a generalized Cartesian oval construction. Those solutions may be perfect for point light sources but, in many practical cases, the approximation of an extended light source as a point source results in loss of efficiency and "smearing out" of the output pattern. Iterative design methods try to optimize point source solutions for extend sources. In contrast to this, and without the need of optimization loops, the SMS method inherently uses the extension of the source as an input parameter to create an optical system perfectly adapted to it. Such systems exhibit performances close the thermodynamic limits.

While the SMS 2D method has generated a number of ultra compact and highly efficient devices with rotational or linear symmetry, SMS 3D has matured into a stable design method for a wide range of applications in nonimaging optics that cannot be solved with systems using linear or rotational symmetry. After overcoming complex obstacles in both programming and 3D surface creation, the SMS 3D method now has matured and reached a level of stability that makes it an every day design tool. Some of the results achieved are presented below.

Up to this point, the SMS method has mostly dealt with two pairs of wavefronts to be coupled. The design results are two profiles or surfaces. Many extensions of this method are being developed, some of which we will presented in the last chapter of this article.

SMS 2D Review

In SMS [1] [2] (simultaneous multiple surface) design procedures, the optical prescription is stated as incoming and outgoing wavefronts. The definition of these wavefronts is sometimes trivial (see example below) but in other cases highly complex: If the design goal is to meet a certain irradiance or intensity distribution, there is no deterministic relation that allows the derivation of exiting wavefronts that create said distribution. However, approximate methods may be applied [3].

In the following section we will review, at a simplified level, the design methods that consist of coupling two pairs of wavefronts that create two generally free form profiles (SMS 2D) or surfaces (SMS 3D) that can be either refractive or reflective. The optical system may consist of any number of surfaces that exist before, after or in between the SMS surfaces. These surfaces are either predefined by the application (e.g. the dome shape of an LED light source or a fixed exit aperture profile) or part of the design, where they are introduced to facilitate the SMS process. The effect of these extra surfaces is taken into account by simply propagating the source and target wavefronts through those surfaces. The resulting wavefronts, now refracted or reflected at the non SMS surfaces, are then used in the SMS calculation. Besides the obvious physical limitations (i.e. etendue conservation [1]), the only condition for a successful SMS design process is the absence of any caustics of the wavefronts to be coupled in the vicinity of the space to be occupied by the SMS surfaces.

In the following example, the edge rays of a 2D light source are to be coupled to two straight exit wavefronts. If the angle between those exit wavefronts is chosen according to the Etendue of the light source and the exit aperture size, this system behaves like a perfect 2D collimator. The input parameters are: Two sources and two target wavefronts, a starting point for one of the SMS surfaces and its normal, the nature of the surface (here refractive) with the index of refraction and two optical path lengths between the conjugated pairs of wavefronts.

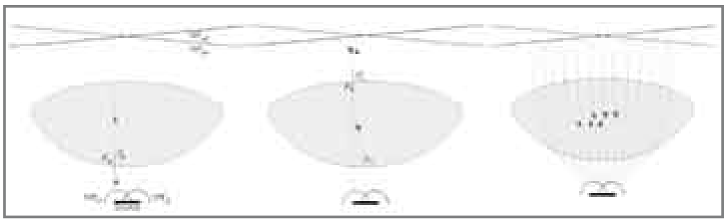

Figure 1: Schematic of design procedure for an RR SMS 2D collimator. The two profiles are calculated starting at a first point P0 (left). All other points follow from this start point in an alternating algorithm.

The profile of the gray lens in Figure 1 shall be designed. The first point P0 and its normal n0 are chosen as input parameters. A ray from the first source wavefront (WFi1) is selected that connects the edge of the source and P0. This ray is refracted. The first exit surface point P1 is found by searching a ray that, emitted from the exit wavefront WFe1, has an optical path length L1. Now a ray from the other exit wavefront WFe1 is refracted at this point, and traced. Point P1 is calculated the same way as before, now utilizing the optical path length L2. Repeating the same steps produces alternating points on the input and exit surface. On the far right of Figure 1 it can be seen, that all rays from each edge of the source leave the lens as rays normal to the exit wavefronts. From the edge ray theorem it is known, that all other emitted rays will not be edge rays and therefore have a smaller off axis angle as the design rays.

The final lens profile is obtained as the minimum order interpolation curve through the SMS points. While strictly speaking the method only controls rays from the two design points, the behavior of rays emitted from other points than the edge points as well as all rays hitting the lens profile where the profile is interpolated between the SMS points are not controlled. In most practical cases, however, SMS designs are "well behaved" in the sense that, firstly, the interpolated profile sections are not distinguishable from a "perfect" profile for rays originating from the design points, and secondly, that all rays emitted from source points that are not design points behave as expected.

SMS 3D Review

The SMS 3D design method has, as the 2D design, as input parameters two pairs of wavefronts, now defined as 3D surfaces and two optical path lengths between the two corresponding pairs of wavefronts. But, instead of a single starting point and a normal as free parameters, now a "seed" curve in space can be chosen that will serve as starting points for the SMS point calculations. SMS points generated using the 4 design wavefronts from a point on the seed curve are called chains. The seed curve can be sampled at as many points as desired to create many chains. The full design is eventually defined by all the SMS points that can be interpolated by two 3D surfaces; one of them contains the seed curve.

In the definition of the seed curves lies an important degree of freedom: It can be obtained by a SMS calculation using for example WFi1/WFe1 and two new wavefronts WFi3/WFe3. This third wavefront pair can consist of a source wavefront emitted from a third point of the source coupled to a third exit wavefront. The full 3D SMS design maintains the coupling of the third wave front pair in surface regions in the vicinity of the seed curve. In surface regions that are not close to the seed curve, this coupling may be lost. This means that a 3D SMS design can, with two calculated surfaces, control three design points, two of them perfectly, one of them approximately.

Imagine a square light source (e.g. an LED chip, Figure 2). The SMS device shall be a dielectric solid, with a metallized back surface (the "X" surface) and a refractive front surface, that will at the same time reflect rays by TIR (called "I") and refract others (called "R"). Those designs are called RXI [9] [10].

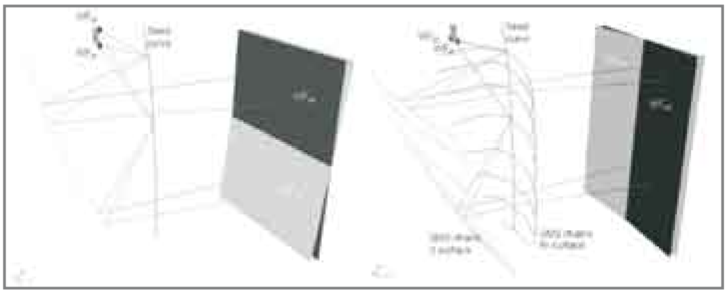

Figure 2: Schematic design procedure for an RXI SMS 3D collimator. Left: "Vertical" wavefronts of source and target are coupled to create two vertical profiles. One profile is the seed curve used to calculate the SMS chains (right).

In total three input wavefronts (e.g. three corners of the chip) and three exit wavefronts are chosen that describe how the light from the chip corners shall be emitted. In the example in Figure 2 all exit wavefronts are planes rotated 5 deg from the z axis, WFe1 and WFe2 horizontally and WFe3 vertically. This RXI shall produce a far field pattern that is an image of the chip of 5 deg vertical and horizontal size. In a first step (Fig 2, left) two vertical SMS profiles are calculated that couple the two "vertical" pairs of wavefronts with each other. One of those profiles will be used as a seed curve for the calculation of the SMS chains (Figure 2, right): Each pair of chains is calculated by coupling the two pairs of "horizontal" wavefronts with each other. The seed curve can be sampled at as many points as needed in order to calculate as many chains as desired. The two families of chains are then approximated (Figure 3, left) by a smooth CAD surface. The RXI shown now directs all rays from the two lower corners of the chip to 5 deg Left/ Right and, in this example, to 0 deg horizontal. Rays from the third design point (an upper corner of the chip) that hit the SMS surfaces near the seed curve will be directed 5 deg down while all other edge rays from the LED chip top corner theoretically are not controlled. However, in many applications, SMS designs are sufficiently well behaved to maintain the desired characteristics for all non design points (Figure 3, right).

The design shown collects the source light within a half-hemisphere. The other half of the light (the light the chip emits upwards) would be captured by a second design procedure done similarly. The two individual RXIs can collect 100% of the light emitted by a light source into a hemisphere or even up to higher off axis angles.

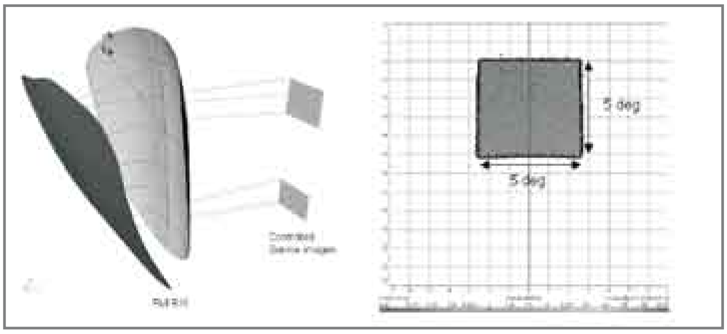

Figure 3: RXI SMS 3D collimator. On the left the two 3D surfaces of the RXI and some source images are shown. On the right: Raytrace of a "well behaved" SMS design with three planar exit wavefronts.

Comparison of Conventional SMS

Conventional design methods design one surface at the time. An example is a freeform mirror used for automotive head lamps. The curvature of every mirror point determines the size and position of the image projected from a small surface element, often called a pin-hole. One design method consists of obtaining a single free-form refractive or reflective surface [4] [5] [6] to solve a prescribed-irradiance problem based on the small-source approximation. This strategy (usually called point-to-point mapping [7]) is well known either for rotational optics, where its solution simply involves the integration of a non-linear ordinary differential equation [8] or for the more general 3D design of a single free-form surface, requiring the solution of a non-linear partial differential equation of the Monge-Ampere type. All of those solutions work well in the small source limit case.

SMS designs control two source points perfectly and a third one partially. The SMS design is fully determined by the choice of the wavefronts and some other simple input values, as described above, with the need of optimization steps.

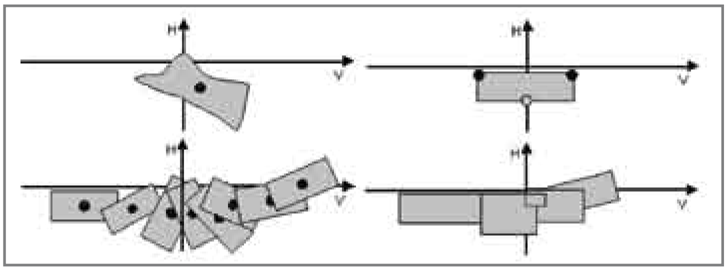

Figure 4: Far field images created by a "pinhole" (upper two graphs) or a set of pinholes (lower two graphs) on the exit surface of a free form optical system illuminated with an extended source. Left: Conventional design: No rotation and distortion control of the images, Right: SMS Design: Size and orientation control of images.

A conventional design only controls one point of the source images. Different sections of e.g. a freeform reflector create far field images of the source of varying size, orientation and distortion (Figure 4, left). The rotation of the images and their distortion may, if the images are large or if the features to be obtained in the pattern are small, seriously degrade the quality of the output pattern. Not so in an SMS design: The pinhole images of the source are guided by 3 source points in a deterministic manner, so that orientation and size can be controlled.

Examples of SMS Applications

TIR-R solar concentrator and LED collimator

The TIR-R system [11] consists of a TIR lens with one flat surface and a secondary lens, both rotationally symmetrical. The secondary lens has a cavity that, filled with an optical coupling gel, holds either a receiver (e.g. a solar cell) or an LED chip as emitter. The two SMS surfaces designed are the reflecting surface of the TIR rings and the surface of the secondary lens. The system has been developed for solar applications to concentrate the solar light onto a small high efficiency solar photovoltaic cell. The theoretical efficiency is 82%. The same optical system, with an adjusted design, can be utilized to collimate LED emitted light with 85% efficiency.

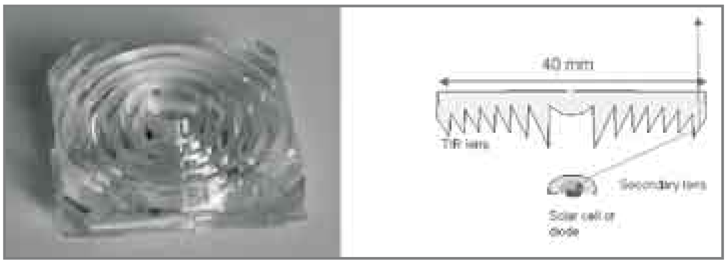

Figure 5: Left: Photo of TIR lens produced by LPI. Right: Working principle of TIR-R combination.

The real-world efficiency of the optical system injection molded with PMMA strongly depends on the surface quality (roughness and deviations from theoretical profile) and the teeth radii of the TIR lens. Since both the convex and the concave vertices are hit by the incident sunlight in the solar application, vertex rounding will reduce the usable surface area and therefore the power transfer to the solar cell.

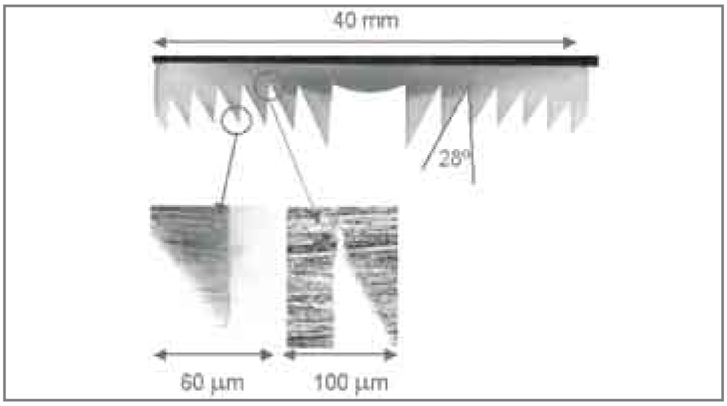

Figure 6: Left: Photo of a TIR lens section and details form its convex and concave tooth vertices.

The TIR shown in Figure 5 and 6, designed for a solar concentrator, has small vertex angles (around 28°) and a diameter of about 40mm. LPI, who owns the IP for and manufacturers the TIR lens, has demonstrated extremely small tooth radii for lenses molded in a prototype tool. The molding tool has been produced by diamond turning. Injected lenses have been cut to examine their profile under a microscope with digital x-y readout. The convex tooth radii have been measured as 5µm in average but some radii are below 3 µm, so that they cannot be faithfully resolved under the microscope. The concave teeth yield 14µm on average and 5µm minimum. Such small radii suppress the efficiency losses of the system due to rounded teeth edges below 1%.

RXI LED collimator

The development of the rotational symmetric RXI is a very good example of the SMS 2D design method. Its striking characteristics have been described elsewhere [10]. In Figure 7 an application as an MR bulb replacement is shown: The RXI collects and collimates the light of LumiLeds' Luxeon Lambertian LEDs of any color. The lens is fitted into a housing that includes drive electronics (input voltage 6-24Vpeak AC/DC) and the LED to make it a full bulb replacement. The RXI lens achieves an extremely tight beam with an opening angle at the physical limit set by the Etendue of the source. The lens diameter is 36mm and its depth is only 9mm.

Figure 7: Left: Photo of a "Chip LED bulb replacement"2. An identical RXI as mounted in the housing is held in front of the full assembly. Right: Radiation pattern of the RXI with a green Luxeon LED. The vertical bars visible in the pattern are caused by the contacts of the LED chip.

The RXI is designed as a nonimaging device to ensure highly efficient light transfer. This is not incompatible with a good image formation although the names imaging and nonimaging suggest an antagonism [15]. The radiation pattern of the RXI in the far-field therefore shows a clear image of the LED chip.

RXI LED headlamp designs

The RXI's design principles laid out in the SMS3D review chapter in this paper, have been applied to design several LED headlamps. These are the first Free-form RXI devices ever designed. Such a design will only be efficient, if it collects light from the entire solid angle of the source emission, collimates the light and forms the beam pattern only by reflection or refraction without the help of any blocking devices or shutters. Very high efficiency is important because high performance LEDs are expensive light sources compared to standard light bulbs and the available LED flux still is at least one order of magnitude lower than that of an ordinary bulb. The RXI is highly efficient, as well as compact and optically pleasing, an important "sales tool" in the automotive field where styling is paramount.

Elaborate calculations carried out by proprietary software create the two free from surfaces that transform the source light into the desired pattern without the use of faceting, shutters or any additional optically active surfaces. Extensive raytracing with in-detail modeling of the light source and prescribed optics verify the designs.

The device shown in the following section represents a typical design of an RXI 3D collimator. RXIs for the low beam and high beam application both for the US market (SAE) and the European market (ECE) have been designed using the 3D SMS method. The dimensions of the device are dictated by the etendue calculations (to limit the vertical or horizontal extent of the pattern) and luminance conservation to achieve the needed hotspot intensities. The RXI has a non active center region because the two reflections of the rays displaces them several millimeters up- or downwards from the center of the light source. This will increase the device size, as the lit aperture size is smaller than the physical aperture of the RXI. A possible design that has been investigated is approximately 27 x 60 x 15 (w x h x d) mm^3 in size for the low beam, where the high beam RXI (not shown) is about 40 x 55 x 17 mm^3. The high beam RXI is wider to meet the hot spot requirements and to better collimate the light in the horizontal direction.

By varying the parameter set that our program uses to calculate the RXI surfaces and by choosing outgoing wavefronts, that are adapted to the low and high beam pattern, we were able to obtain "legal" designs for both the low beam and high beam RXIs. In detail raytraces, the designed elements prove their performance. The low beam yields total optical efficiencies (defined as the ratio of flux projected onto the road in +/-30deg horizontal and +/-10deg vertical window divided by the full source flux) of 80%, assuming a reflectivity of 93% for the metallized surface, and anti reflection coatings on the refractive surfaces. Without anti reflex coatings 75% (68% with cover lens) is reached.

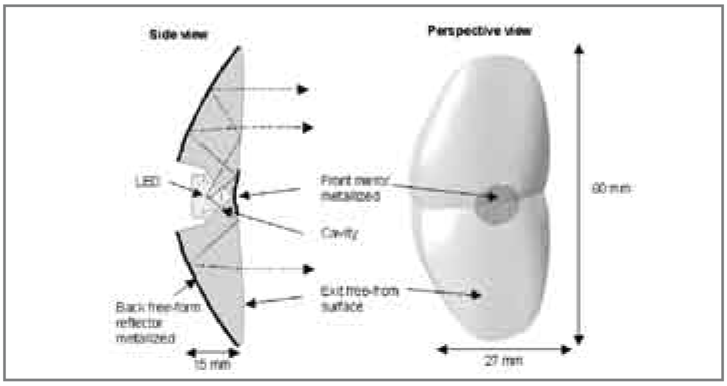

Figure 8: Schematic view of a 3-D RXI (for low beam).

The high beam RXI is even more efficient: Up to 85% with and 80% without anti reflex coating can be achieved. The low beam RXI meets the regulations FMVSS108 Table 17 with 8 LEDs (and 8 RXIs) of 80lm each. It also passes the legal gradient values as defined in FMVSS108 easily. For the high beam, an additional 8 LEDs of 80lm are used. Both sets of RXIs together meet the high beam specifications. The hotspot of both functions combined is 50000 cd. Prototypes for both low and high beam have been manufactured that perform with almost the theoretical efficiency. Values of 75% efficiency for a diamond turned low beam element without anti reflex coatings and 84% efficiency for an injection molded high beam element with anti reflex coatings have been measured. Raytraces had predicted efficiencies within 2% of the measured values.

The low- and high beam units can be arranged in many different configurations to meet designer's expectations. The final number of RXI modules is inversely proportional to the available flux of the LED.

By choosing different design parameters and wavefronts, an RXI similar to the shown design in appearance and size, has been designed to meet ECE low beam and high beam specifications. Because of the more demanding gradient specifications of the European regulations and the lower stray light levels (light projected above the horizon), those designs must exhibit even better light control than the SAE versions. The SMS design has therefore been refined to create more precise 3D surfaces that reduce ray angle deviations from the theoretical wavefronts used for the design. Raytraces demonstrate the success of those designs; however, as the gradient is formed by imaging the LED chip edge, placing tolerances on the luminance distribution of the LED chip within its package, the RXI lens must be very tightly controlled.

Outlook onto future LED lamps designs

A single LED Headlamp will be possible as soon as there will be a chip available that produces more than 500 lm. In the hypothetical case that an LED with chip dimensions similar to today's LumiLeds Luxeon LED would be available, a full low beam headlamp could be of the size of a single RXI of 25 x 55 x 14mm^3. Smaller LEDs with the same flux would lead to a linear reduction of aperture size. However from a safety and design standpoint too small aperture sizes may not be desirable.

Besides the inherent advantages of LEDs (their longevity, instant turn on, "whiter" color, and smallness), very bright and small LED chips enables the optical designers to create beam patterns of unsurpassed beam quality, in terms of brightness, uniformity and light control. The SMS method offers the necessary precise light control needed to realize those future designs.

Incandescent SMS headlamp

Another successful application of the SMS 3D method it the design of a low beam and high beam headlamp that, as conventional headlamp designs, uses a halogen bulb as a light source. The optics, however, doesn't consist of a typical single free form reflector or a projector system as today's headlamps, but of a complex lens, that redirects the light from the source by refraction as well as by metallic mirror surface and total internal reflection. As the optical system envelopes the light bulb, the collection efficiency is much higher than of conventional head lamps. Because of the perfect image control of the SMS method, all filament images are kept horizontal all over the exit surface of the optical system. This allows us to reduce the vertical height of the system in comparison to conventional designs. The result is a headlamp that is more compact both in exit aperture size and depth and more efficient in terms on flux projected on to the road than today's best halogen bulb headlamps.

Because of the proximity of some parts of the design to the hot light bulb, glass has been chosen as lens material. In consideration to our customer, we are unable to reveal more detail on this development at this time.

UFO LED collimators

High power LEDs (e.g. the LumiLeds Luxeon LED) today put out up to 80lm of white light. Those flux values are made possible by relatively large LED chips that, in the case of the mentioned LED, measures 1 x 1 x 0.1 mm^3. Because of the Etendue conservation, it is not possible to incorporate a collimator into an LED dome (e.g. of mm diameter) that would at the same time be efficient and produce a small collimation angle of the output beam. Therefore, a round dome is placed over the LED chip and the collimation of the now near Lambertian light source is left to external lenses. Purely refractive systems are unable to cover the full solid angle of the emitted light. The collimation of the LED is a classical problem of nonimaging optics- for example the CPC [1] is a well known solution to this problem. However, mass producible metallic surfaces don't reach very high efficiencies and CPCs, for small collimation angles, are very deep. The aforementioned RXI is today's most compact collimator, but it also uses metallic reflection. For mass production, besides the fact that no more then 90% reflectivity at each ray interaction is achievable, this metallization means added cost.

TIR reflection is the most efficient reflection process and it doesn't require additional coatings. Today's modern tool making (diamond turning) and injection molding processes enable the reproduction of optical plastic surfaces that achieve the necessary low surface roughness and flatness to ensure full TIR. Several LED collimators using TIR exist on the market, but they often exhibit low efficiency and high depth, so that the associated large plastic volume makes injection slow and expensive. Also, their minimum diameter is relatively large if high collection efficiency is to be maintained.

Here we present a new class of LED collimators, called "UFO", that drastically reduces the plastic volume. The small wall thickness speeds up plastic injection cycle times and lowers cost. At the same time the design is extremely efficient: Raytracing results have demonstrated efficiencies as high as 92%, so that all losses can be attributed to Fresnel reflections at the input and exit surfaces of the device. If anti reflection coatings were applied, efficiencies of almost 100% could be achieved.

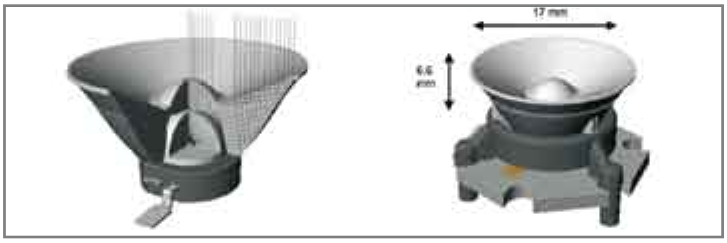

Figure 9: Schematic views of a UFO LED collimator, on the left with a Luxeon emitter and ray trajectories, on the right with a plastic holder to place the LED over the standard Luxeon Star LED.

The UFO design utilizes several sections of different ray trajectories. All surfaces have tailored profiles. The central section captures the LED light emitted close the optical axis and collimates it by two refractions. The second section, of greater off axis angles, is an "RIIR" section: The light is first refracted, then reflected (TIR) at the exit surface, another time reflected (TIR) at the back surface and then refracted at the outer section of the exit surface. Both reflections are TIR. The third section works as "RIR" (Refraction, TIR, and Refraction) and collects the light emitted to large angles.

A variety of designs have been derived with diameters as large as 36mm to achieve very narrow collimation and as small as 14mm, much smaller than it would be possible for conventional collimators without compromising efficiency. As a standard product, to be marketed soon by LPI, a diameter of 17mm has been chosen, as a compromise between collimation angle and compactness. (For comparison: the Luxeon Star LEDs are provided attached to a hexagonal PCB of 18mm width). The lens itself is only 6.6mm tall, making very compact assemblies possible. Comparable LED collimators available on the market have slightly larger optical apertures (approximately 18mm). They are approximately 10mm tall (see Figure 10), almost 50% taller than the UFO. Their plastic volume is almost three times higher than the UFO.

Figure 10: Schematic views of two commonly available Luxeon collimators (left and center) and the LPI UFO (right). All three designs have similar exit apertures and collimation angles. The two designs on the left have plastic volumes of approximately 1500 and 1300 mm3 respectively, while the LPI UFO (right) has a volume of about 500 mm3.

While the collimation angle of the UFO for the different Luxeon LED colors varies between 8° and 10° FWHM, the efficiency is 90% for all Lambertian Luxeon LEDs. In order to place the UFO lens over the LED and onto the PCB, various holders have been designed that fit over the Luxeon star 1W and 3W, and can also fit directly onto a PCB if the naked Luxeon emitter is used.

Different UFO models for wider collimation angles but with the same footprint, size and exit surface are being developed by LPI. Those designs exhibit flat intensity patterns and well defined cutoff angles.

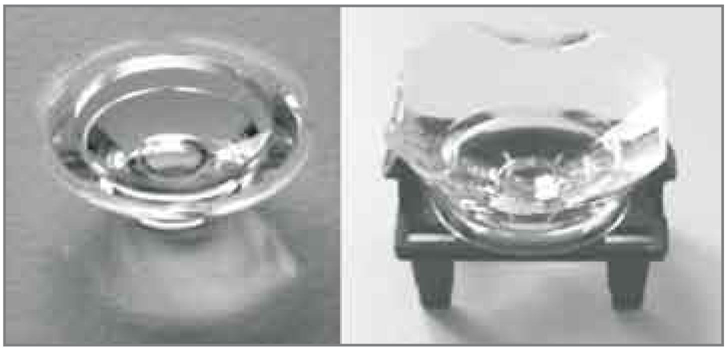

Figure 11: Photo of other UFO LED collimators, designed for specific applications. The lens on the left has a diameter of 18 mm, the right one 30 mm lateral dimension.

Single piece zoom optics UFO LED collimator

For various illumination applications zoom lenses are employed. Classically this is solved by moving the incandescent bulb along the optical axis out of the focus of a parabolic reflector. However, in most cases neither the focused position forms a bright, well defined and homogenous hotspot, nor is the wide beam free of radial intensity variations noticeable as dark or bright concentrical artifacts. Moreover, if a source is moved out of the focus of a parabola, in many cases a dark center spot occurs.

In order to create a LED collimator with a zoom function, a secondary lens, after or before the collimator, can be employed, that can either rotate or move laterally or longitudinally to open the narrow beam to form a homogenous wide beam. We have employed a different concept: We use the UFO itself to perform this function without the need of extra elements.

A particular design example has a diameter of 35mm. The UFO is designed in a way to work as a collimator in one position, and, when moved 2mm away from the Luxeon LED, opens up the beam in a very homogenous way with almost perfectly flat intensity in the far field up to 40 ° off axis angle. The design uses tailored surface sections that are illuminated differently in the two positions of the lens by the three ray bundles of the UFO. The efficiency of the device varies between 80% and 90% at wide and narrow beam positions, respectively. Even between the two different design positions, the device doesn't show excessive intensity variations in the form of concentric artifacts. The central part of the distribution shows a continuous drop in intensify towards the wide beam position without any dark center formation.

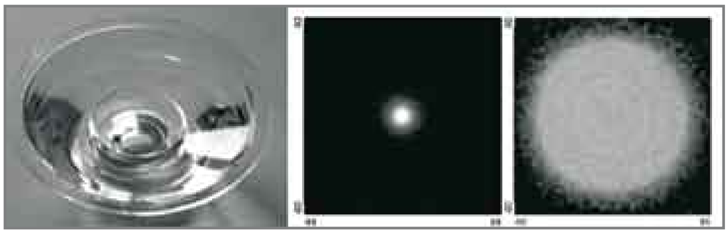

Figure 12 Left: Photo of UFO Zoom lens. Center: Raytraced simulation of the narrow beam with 6° FWHM. Right: Wide beam simulated with flat intensity and 80° FWHM. Raytraces are represented in Munsell "lightness" coding.

Future SMS Applications

Compact SMS 3D integrators

Integrators have been employed to homogenize the illuminance of projection systems. Such integrators normally consist of two arrays of micro lenses that have the same focal length and are at the same time separated by their focal length. The intensity distribution of the second lens is an image of the illuminance distribution on its focal plane. If the lens pitch is small compared to the distance from the source, the illuminance to be imaged by one micro lens will be almost constant, so that the outgoing intensity pattern will also be uniform. The integration zone can be designed to include the entire emitting zone of the source and the output will be independent of any luminance variations in this zone. If the integrating zone is chosen larger than the source size, the output will stay unchanged, even it the source moves within this zone, so that the design can be made tolerant to source positioning errors.

As SMS designs work close to the light source, they may be more dependent on positional tolerances and the illuminance distribution of the source than conventional designs that use larger optics farther away from the source. In order to combine the compactness of an SMS design with the robustness of a conventional design, we have designed free form micro lenses that can be combined with SMS designs without the need of extra integrating elements. These designs can integrate in one or two spatial directions. A typical application where the integration in one direction is desirable is the automotive headlamp, where a well defined vertical cut-off has to be achieved. In the case of the ECE specification, the intensity may have to drop from 30,000cd to almost 0 in little more than 1deg vertical variation, but the horizontal pattern is very wide and has a smooth roll off. An SMS integrator design can produce a vertical cutoff that is independent of the source illuminance distribution and, depending on the design parameters, also tolerant to vertical source positioning.

A different application, where integration in two spatial directions is necessary, is the color mixing of light from an RGB light source consisting of three or more sources that are distributed over different positions (e.g. an RGB LED with 3 chips in one housing). We expect SMS integrator devices to be developed in the near future that collimate light from such an RGB source while maintaining the same intensity ratio amongst the three sources and therefore the color of the combined light at any point in the intensity pattern.

SMS condensers

In digital projection the most commonly used light source is an arc discharge lamp. The full optical train consists typically of light source, elliptical mirror, glass mixing rod to achieve constant illuminance at the exit surface of the prism, LCD micro display and optics to project an image of the LCD display onto a screen. The achievable brightness depends on all elements but the condenser may be the most critical.

The typical elliptical mirror collects a certain fraction of the fully emitted light and forms arc images on the entry aperture of the light mixing rod. The size of the images varies (in meridian length and sagittal width) from point to point on the condenser exit surface and the images rotate due to the rotational symmetry of the mirror and the arc. Due to the rotation of the arc images, conventional condensers perform worse when the target aperture is not circular but rectangular, especially when the aspect ratio is high as for a 16:9 picture format. A mixing rod of larger diameter would increase the efficiency but this would have to be combined with a larger display, at a prohibitive cost.

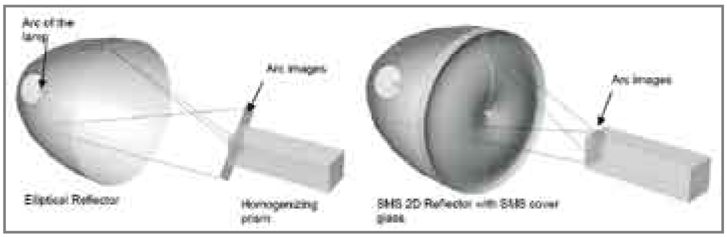

Figure 13 Digital projector condenser, left: Conventional design with arc imagines of varying size, on the right an improved design with constant arc image sized using a tailored reflector and glass cover profile.

As en ellipse perfectly transforms rays emitted form on of its focal points onto the second focal point, all other points are not controlled. An SMS 2D design controls two points (the extreme ends of the discharge in this case) that can be mapped onto a circle of the mixing rod entrance aperture to control the meridian image size. This design (Figure 13) would use the mirror surface and one of the surfaces of the lamp glass cover as SMS surfaces of rotational symmetry with tailored profiles. A similar solution has been described before, although in the limit of a small source [1] [13]. Such a design results in a noticeable increase of in-coupling efficiency. However, from the description of the SMS method above, it should be clear that a full SMS 3D design would be even more beneficial as it also controls the rotation and the sagittal image extension. Such a design would not have rotational symmetry but it can project source images of constant positional and aspect ratios exactly tailored to the mixing rod dimensions.

SMS imaging

The SMS method has been developed for nonimaging applications but the method can be applied to imaging solutions: If the input and exit wavefronts are spherical (for object and image points in the near field) or flat, for points at infinity, one pair of points will be perfectly imaged into two image points. The well known Cartesian converts a parallel wavefront into a spherical wavefront. A single surface that converts one general input wavefront into a given exit wavefront can be understood as a generalized Cartesian oval [14]. It is not trivial, however, that two surfaces (e.g. of a lens, see Figure 14, center) can convert two inputs into two exit wavefronts, and that n SMS surfaces will image n points into their conjugate points. With many points imaged perfectly, one can hope that all adjacent points, and eventually a complete area inscribed into the design points, may be imaged with very good quality onto the imaging plane. Conventional optics, consisting of spherical surfaces, doesn't image even a single point perfectly because of spherical aberrations. In order to improve a lens design, often some paraxial aspheres are added. Conventional optics, however, fail to work well for non paraxial rays because the optimization methods start off from the paraxial regime and spherical surfaces. In some cases large off axis angles are desired, e.g. the imaging section of projectors in order to minimize the projector-to-screen distance. Conventional lenses are limited to projection angles of about 30-40°.

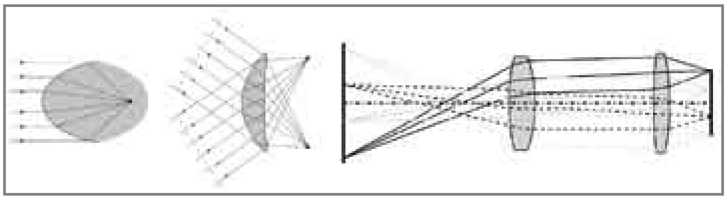

Figure 14: Left: A Cartesian oval focuses a parallel ray bundle into a point. Center: An SMS lens can focus two wavefronts into two different points. Right: Two SMS lenses can focus four objects into four imaged points.

SMS 2D concentrators have been found to work as ultra-high numerical aperture imaging devices [15]. Also, achromatic aplanatic aspheric doublets [16], designed with SMS 2D, have been demonstrated. In general, SMS lenses don't have any paraxial limitation and can therefore be designed to large off-axis ray angles. A projection system with SMS surfaces could therefore be extremely compact as projection angles up to 85 deg can be realized.

The possibilities of SMS 3D in imaging optical systems are still being evaluated but the added wavefront control can make these much more powerful than SMS 2D designs. However, the resulting free form surfaces may be a challenge if applied to glass optical elements but in reflector designs, production technology has reached a level of accuracy that makes free form imaging possible.

Summary

The SMS 2D design method has been applied for many practical devices, some of which are presently being mass produced. The much more complex SMS 3D method has reached a maturity and unsurpassed light control capability that makes it the tool of choice for complex illumination tasks and, in the near future, for certain imaging problems. The SMS 3D method, applied in several automotive LED headlamps designs, has proven to produce highly detailed intensity patterns, while at the same time reaching the highest efficiencies and ultra compact dimensions. A future stage in SMS 3D will be the design of three free-form SMS surfaces to perfectly control three wavefronts to enable even a higher level of control of the output beam quality. SMS 3D devices are expected to be mass produced soon and will appear in many different applications ranging from illumination to collimation, condensers and image projection.

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All optical devices shown are protected by patents awarded, in allowance or pending. See under patent list.

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Patent List:

SMS 2D Design method, RXI 2D (rotational symmetry): 2D SMS patent (issued): "High Efficiency Non-Imaging Optics" Patent # 6,639,733, Issued Oct. 28, 2003. Inventors: Juan C. Minano, Pablo Benitez, Juan C. Gonzalez, Waqidi Falicoff and H. John Caulfield.
RXI 2D (rotational symmetry), UFO, UFO Zoom: Air-gap RXI and CIP continuance (in allowance): "Compact Folded-Optics Illumination Lens". Inventors: F. Muñoz, Juan C. Minano and Pablo Benitez.
SMS 3D Design method, RXI 3D, Incandesent SMS 3D; 3D SMS: "Three-Dimensional Simultaneous Multiple-Surface Method and Free-Form Illumination-Optics Designed Therefrom" (pending). Inventors: Pablo Benitez and Juan C. Minano.
TIR-R: J.C. Miñano, P. Benítez, "Device for concentrating or collimating radiant energy", PCT/ES00/00459

Plastic Optics Enable LED Lighting Revolution

> Tomi Kuntze, Managing Director, LEDIL Oy

Only some years ago LEDs were predominantly used as tiny marker lamps in electronic devices. The recent rapid development in semiconductor and packaging technologies has quickly turned LEDs into powerful lighting components, capable of replacing existing light sources, such as bulbs, halogen lamps or even highly efficient fluorescent tubes.

So far, the adoption of LED technology has been strongest in architectural lighting, signage, automotive lamps, mobile phones and displays. In everyday life, more and more public places such as building facades or bridges are being illuminated by colorchanging LED systems. The next major area for penetration of the LED technology will be in general lighting. An essential enabler for LED lighting revolution over the coming years is a clever use of optics to collect and shape the light from the LED package. In the following article we go into the details of how to do it by means of advanced plastic optics.

Illumination Engineering

Applications of optical engineering related specifically to illumination systems are often called illumination engineering. As illumination engineers, who wish to design a good LED lighting system, we need to pay attention to many of the following important issues:

- Which LED and which color is most suitable for this application?
- What is the optimal type of light distribution for this application?
- What is the CRI value needed – is brightness more important than a good CRI (Color Rendering Index, describes color appearance)?
- How uniform shall the illumination be, both in terms of brightness and color, over the object to be illuminated? Do you allow any shadows or other inconsistency in the projected beam of light? How consistent shall the quality of the light (intensity, color) be over time?
- Do we need to choose any special materials or components due to the environment where the system is assembled in?
- Do we need any modularity of the system components?
- What kind of flexibility is needed from the system setup, to enable assembly of it next time in another place?

The list above can be endless, which shows the complexity of requirements for good illumination engineering. It also means that a LED lighting system and its components always are results of various compromises. There seldom is a way to fulfill all the requirements at the same time. If it was done, it would often mean a system that is too complex to use, too difficult to manufacture or too expensive. Therefore, let us take a look at the various aspects of a best possible compromise, each in turn, and try to figure out, how we can create a best possible optical system for LEDs.

Figure 1: LEDIL CAT lens for Street lighting.

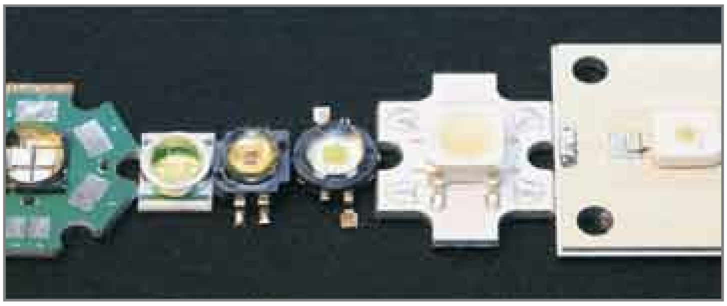

Figure 2: LEDs as light sources vary much from each other. The same optics cannot be used for several LEDs without jeopardizing the performance.

Figure 3: LEDIL FLARE lens for Luxeon K2 and LEDIL FLARE-C lens for Cree XR-E show how different light sources lead to different lens design, with the same illumination specification.

Challenges with LED as a Light Source

Even as LED packages have developed much during recent years, there does not seem to exist any common idea among LED manufacturers, what an optically good LED package should look like. All of them are different from each other and only a few of them have been designed for easy adoption of secondary optics. Many of them have been designed to get a brightest possible beam out of the LED itself, without thinking how the beam can be used in the following step: secondary optics.

In all LED packages the chip has a square or rectangular shape. If a conventional, highly efficient lens is used and this lens has been designed with an idea to make a most accurate image of the object in its focal point, the illumination result is the same square or rectangular shape of the LED, with all chip details projected on the object to be illuminated. Nobody likes it, as the first rule for an illumination engineer is to make a beam that is smooth and pleasant. Therefore, the challenge is how to maintain the high efficiency of a conventional lens, but at the same time get rid of the square and make a round shape instead.

Another challenge is, how to achieve an even white color on the object, even if the LED used does not emit uniformly white light? The problem here may be a result of variations in the blue LED underneath the phosphor layer, unevenness of the phosphor layer or some die manufacturing details. In many cases, a secondary optics has to heal problems that actually are LED related, but become apparent when the LED is exposed to a secondary optical system.

A third main challenge for optics is multiple-die LEDs, which have a great number of chips, populated densely, close to each other and covered with a common phosphor layer or dome. It is very difficult to develop optically efficient and visually pleasing optics for such LEDs. The reason is that most illumination optics development is based on an idea of a point light source. Having e. g. 4 x 4 dies makes it impossible to use this principle in design, as dies are too near to each other to be seen as separate, but too far away from each other, to be seen as a point light source. The final result is that such light LEDs cannot be used in applications where a good collimation and narrow light distributions are needed.

Main benefits for LEDs, when compared to other light sources, are the directional light they give and the relatively small size of the light source. In that sense LEDs easily outperform all other light sources, such as bulbs and fluorescent tubes.

Optimization with Regard to Light Source Characteristics

Some companies have gone so far in the standardization of their lenses that they have decided to treat all LEDs as similar light sources and offer the same lens for many LEDs. In my opinion, this is not possible, nor rational to do, as every LED is very different from each other. As a clear evidence of this difference I show 3 different simulation pictures, which show the illumination result, when a lens, optimized for LED "A" is put at its correct focal length, but used in combination with lenses "B" and "C". You can see how the well controlled beam in "A" changes to a scattered plot in "B" and "C".

E.g. LEDIL designs and optimizes every optical system with regard to the LED it is going to be used with. It guarantees that a full efficiency both in terms of power and visual appearance is achieved.

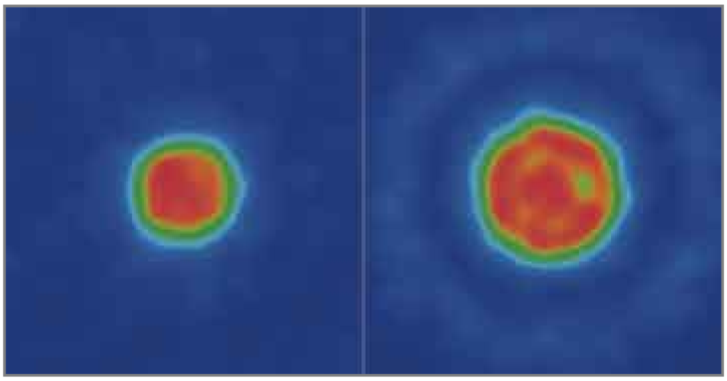

Figure 4: Light distribution of a lens, with the light source it has been optimized for (left), and the same lens, positioned at a correct focal point, but using a LED, which the lens has not been designed for (right).

Figure 5: An example on the use of a clip-on sub lens to change illumination characteristics of a lens.

Figure 6: An example of modular lens system, with adhesive tape fastening, is the square lens series with more than 50 different versions (light distributions and optimized for various LEDs).

Basic Optic Types

LED optics can be categorized in e. g. lenses, reflectors, combinations of them and systems of multiple lenses or reflectors. It cannot be claimed that some of them would be better than another. It fully depends on the application and its requirements.

Generally speaking, however, lenses are more efficient in shaping the beam than reflectors. The main reason is that light in a lens travels through at least 2 surfaces (often more), before getting out of the system in the desired angle, while for simple reflectors a part of the light gets out without ever hitting any optical surface. On the other hand, every time light enters or exits a surface it looses its efficiency, which speaks against complex lens systems and favors reflectors.

Most companies offering LED optics base their optical idea on collimating the light from the LED with a standard collimator lens design, spreading the light on the top surface of the lens in the angle needed. The quality of the resulting beam depends on how accurately the LED is studied, and the degree and method of inter-connecting the optical surfaces to each other.

Free Form Lenses

A more advanced idea is to freely modify all the optical surfaces, when having an accurate model of the LED and knowing what the resulting beam shall look like. This kind of optical system is called free form system. Free form does not mean that a computer calculates the optical geometry with given input and output conditions. For good free form optics there is also a structured, wellconnected underlying optical concept, which the illumination engineer in charge has created. Clear benefits with free form optics are e. g. good modeling of LED resulting in great accuracy, high optical efficiency, controlled beam quality and a smaller physical size.

Reflectors

Reflectors have been used as optical element for a longer time in history than lenses. Reflectors are easy to manufacture, therefore cheap. A common denominator for all reflectors is a relatively large opening angle, i. e. a large part of the emitted light from the LED gets out of the system, never hitting the reflector surface. The phenomenon results in a relatively large area of scattered light around the so-called hot spot area. Obviously, the angle can be minimized by increasing the height of the reflector, but it seldom is possible achieve a great extent of control. Reflectors often show a light distribution, which has a higher peak and less smooth curve than what is the case for a lens of the same size.

Combinations

Combining reflectors and lenses in one optical system is a challenge, as the optical functioning of them is very different and a combination easily results in a less efficient system than planned.

Combining lenses in a system or doing the same with multiple reflectors may be used with success. As an example of a flexible and cheap optical system using lenses, LEDIL's series of lenses use one and the same base lens that can be modified with add-on sub lenses, to change the illumination pattern.

System Thinking, Integration, Platforms

An important feature, when designing an illumination system, is to develop a modular system that can be easily adapted for different applications. When it comes to optical components, we have chosen a few mechanical optics platforms, which we modify to their optical geometry, but not to their mechanical dimensions. The end user can feel confident that he always finds a standard component of a certain size, with different optical characteristics and the same size and optical choices for several, different LED types.

Another important feature is the shape of the components and the easiness of integrating them in the surrounding mechanical systems of an illuminator. As an example of a standard platform and shape is the LEDIL square lens series, with 50 different optical units with the same size and shape. Furthermore, this component can also be supplied as separate parts, which enables the customer to replace a part of e. g. the lens holder construction by the structure of his illuminator.

In general terms, all kinds of mechanical features can easily be integrated in a plastic optic – let it be a lens or reflector or a group of them. As examples of features used in several lenses are: adhesive tapes, threads, snap hooks, pins, screw holes and welding features.

Optical Materials

Without going deep into the materials science, it is essential to give a quick note on materials to be used in advanced optical systems. There is a difference in materials, which often cannot be seen with bare eyes. Most of the LED lenses of today are manufactured of PMMA (acrylics) or PC (polycarbonate). There are special applications requiring COP or PA12 materials, but they are rare. A special attention should be paid to the variation within materials supposed to be "PMMA" or "PC" only. There are hundreds of different materials in these material groups and only a low percentage of them fulfill the criteria of being excellent for advanced plastic optics. Care must be taken of to insure good dimensional accuracy and stability, heat resistance, UV resistance, molding parameters (parts without stress), chemical resistance etc.

The Future Is Bright

Finally, we want an answer to the ultimate question: why is it beneficial to use plastic optics and why is a good optical solution the key to LED lighting revolution? The answers are many, but they all are simple and understandable:

Price. No other material has such a high price/performance ratio as optical plastic. Glass outperforms plastics in a few features, but overall, the list for plastic is overwhelmingly long.

Versatility. Plastics are the only optical materials, which can have numerous mechanical features integrated in the optical system. Different plastic materials can be used in different environments. Different plastics can be used to achieve different optical effects.

Performance. Only plastic optical systems have made LED flashlights possible in big volumes. The same can be said for most of the automotive LED applications – both interior and exterior. Without plastics and optics it would have been impossible to fulfill the requirements of these lighting systems.

Starting in a big scale in a few years, we will all see a LED lighting revolution take place in our homes, offices and public places. Take a close look at all of the solutions. I can guarantee that you will see a great number of plastic optics there, too, plastic optics – the enabler of LED Light Revolution. ■

New Drive Circuit Supports Wide DC Input and Output Range

> Bernie Weir, Director of Applications, ON Semiconductor

There are many reasons why lighting designers are looking to adopt LED technology. Long operating life in the range of 50,000 hours, for example, helps to reduce ongoing maintenance costs, while instant turn on, even at temperatures as low as -40°C, is not possible with some other light sources. LEDs are small enough that they can be integrated into a wide variety of applications and, as a higher efficacy source of light than traditional incandescent, halogen and fluorescent, can help designers address commercial and environmental pressure to reduce power consumption. What's more, there are ongoing advances in efficacy as illustrated in recent announcements from manufacturers such as Cree and Nichia of LEDs capable of delivering 130-150 lumens/Watt in the lab. Finally, technology and manufacturing advances are helping the commercial argument for solid state lighting by continually driving down cost per lumen.

In order to achieve specified brightness and color it is critical to drive LEDs with a constant current. For high brightness power LEDs currents can range from 100mA to 1500mA, although 350mA is a common value. Table 1 shows manufacturers' data for several product families, which has been used as the basis for creating minimum and maximum voltage for a generic LED as shown. The output voltage swing for strings of three to six of these generic LEDs is also included for reference. From this data it is apparent that in normal operation variations of ±30% can be expected.

Figure 1: Example of a series string of LEDs in one package (OSRAM Ostar).

There are numerous ways that LEDs may be combined in series or series/parallel strings. Take, for example, a typical interior automotive lighting application requiring 200 lumens. Depending on LED selection, this requires a series string of three to six LEDs. Figure 1 shows a multi LED device package. To drive any LED combination that may be envisaged, an efficient, high density, cost effective constant current converter with both a wide input (8V to 19V) and a wide output (6.9V to 30V) range is required. A pure buck or a pure boost switching regulator topology is not sufficiently flexible. What is proposed for the LED driver, therefore, is a current regulated, non inverting buck/boost converter. A high side current sensing scheme is used as it allows the LED string cathode is connected directly to ground. Also, to maximize converter performance, a sensing scheme having a low loss (e.g. 200mV) is required. The schematic of the LED driver is illustrated in Figure 2.

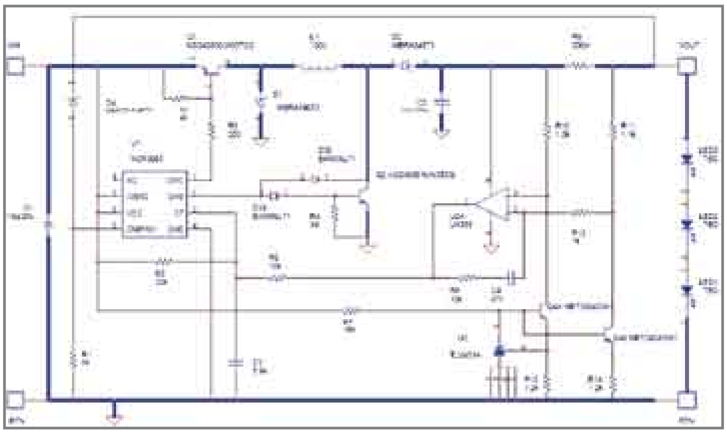

Figure 2: Schematic of the new LED driver circuit.

Theory of Operation

The simplified power stage is shown in Figure 3 for clarity. To minimize power dissipation in the power circuit, low ripple current is required. So the converter is operated in a continuous current mode (CCM).

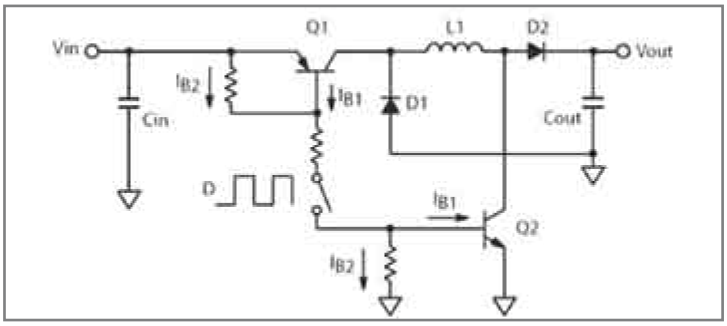

Figure 3: Simplified power stage of the driver.

For this analysis, all power components are assumed ideal. Switches Q1, Q2 turn on for time D*Ts (D duty cycle, Ts switching period) charging inductor L1 from input Vin. When Q1 and Q2 turn off, diodes D1, D2 deliver the inductor energy to the output Vout. For the inductor flux (V*µs) to remain in equilibrium each switching cycle, the V*µs product across the inductor during each switch interval must balance, as shown in equation 1.

$$V_{in} \cdot D \cdot T_S = V_{out} \cdot (1-D) \cdot T_S \qquad (1)$$

Rearranging equation 1, the voltage gain of buck boost is given by :

$$V_{out} = V_{in} \cdot \frac{D}{(1-D)} \qquad (2)$$

Varying the duty cycle will vary the output such that when D is below 0.5, the converter is in buck mode, when D is above 0.5, the converter is in boost mode and when D equals 0.5, the voltage gain Vout/Vin is unity.

The ripple current in the inductor is given by expression:

$$\Delta I_{L1} = \frac{V_{in} \cdot D \cdot T_S}{L1} \qquad (3)$$

Assuming Vin = 12V and D*TS = 0.5*5µs, a value for L1 of 68µH in equation 3 will maintain +/-30% ripple current in a 700mA application maintaining CCM operation. MOSFETs or BJTs can be selected as the primary switches Q1/Q2. NSS40500UW3T2G and NSS40501UW3T2G from ON Semiconductor's e²PowerEdge family of BJTs were chosen for cost/performance criteria. They feature ultra low saturation voltage and high current gain capability (Figure 4).

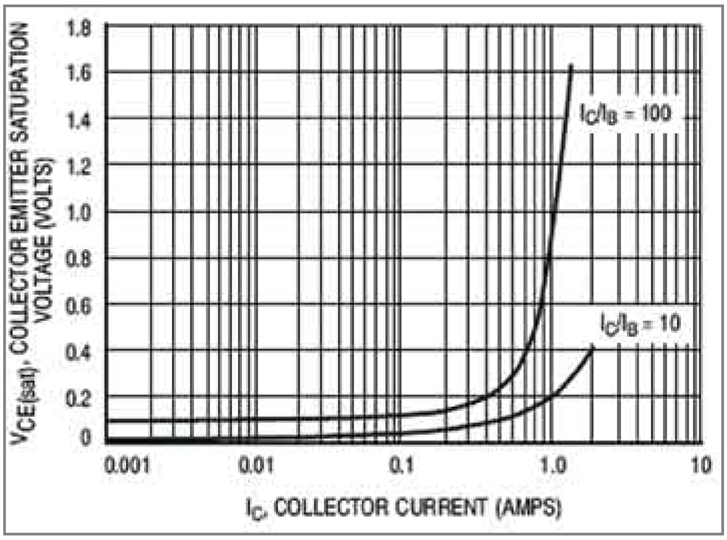

Figure 4: Saturation and current gain capability.

Turn on, turn off, saturation voltage and storage time of a BJT are controlled by the magnitudes of turn on IB1 and turn off IB2 base currents. The drive currents are identified in Figure 3. The values of the base drive resistors R2, R3 and R4 in the schematic may be adjusted to optimize performance. The efficiency of the converter can be improved if the storage time of Q2 is less than Q1. The reasons for this will be discussed later. Q2's storage time can be reduced if it is held out of saturation by the addition of D3a/b shown in Figure 3. Once Q2 is near saturation, additional base current flows through diode D3a and into the collector junction. This diversion of base current IB1 reduces the stored charge in the base region and allows a faster turn off. Typical TS of 1.5µs is reduced to a few hundred nanoseconds.

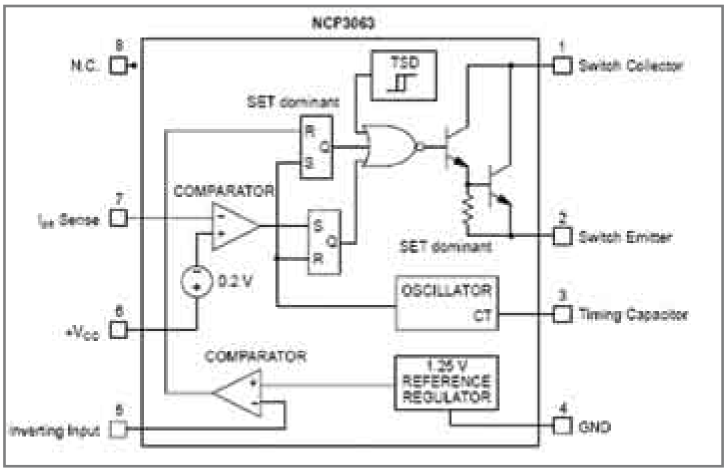

Figure 5: Functional block diagram of the used controller, NCP3063.

This device consists of a 1.25V reference, comparator, oscillator, an active current limit circuit, a driver and a high current output switch. In its traditional operating mode, the NCP3063 is a hysteretic, dc - dc converter that uses a gated oscillator to regulate the output voltage. Voltage feedback from the output is sensed at pin 5, and gates the oscillator on/off to regulate the output. The oscillator frequency and off-time of the output switch are programmed by the value selected for the timing capacitor, CT. CT is charged and discharged by a 1 to 6 ratio internal current source and sink, generating a ramp at pin 3. The ramp is controlled by two comparators whose levels are set 500mV apart. In normal operation, D is fixed at 6/7 or 0.86. The "gated oscillator" mode is used to protect the LED string if a LED fails 'open". A zener diode between Vout and pin 5 will clamp the output at a voltage VZ + 1.25V.

The NCP3063 can also operate as a conventional PWM controller, by injecting current into the CT pin. The control current may be developed either from the input source, providing voltage feed-forward (via R5) or from the output current sensing circuit (via R6). In both cases the slope of the oscillator ramp changes causing D to vary. In Figure 2, the current sense resistor R9 is placed in series with Vout, to satisfy the high side sensing requirement. The bandgap reference U3, together with dual NPN transistors Q4a,b and R13, R14 create two equal current sinks. If U3 is a 1.25V bandgap and R13, R14 equal 1.24kΩ (1%) two 1mA current sinks are formed. Resistors R10, R11 level shift the current sense signal IOUT*R9 to satisfy the input requirements of U2. To create a 210mV reference for the current loop, the expression 1mA * (R10-R11) = 210mV must be satisfied. Hence R10 is selected to be 210Ω larger in absolute value than R11. Current regulation is set by the equation Iout * R9 = 210mV. If R9 is 0.6Ω, the programmed current is set for 350mA. The difference between the 210mV set point and the current sense is amplified by U2 to create an error voltage. This error voltage and R6 drives a programmed current into the CT pin to regulate the LED current.

Because the converter is switching at 200kHz, MLCC capacitors in SMT packages can provide cost effective filtering. Low value MLCC capacitors (10µF) have very small ESR (2mΩ) and ESL (100nH) values. When used in single or parallel combinations they form a "perfect" capacitor. Ripple voltage is due only to charging and discharging the capacitor by the inductor. Two 10µF, 1210 capacitors are employed across the input and output of the driver. The ripple voltage across the input capacitor = D*Ts*ΔI (L1) / Cin. The ripple voltage developed across the output capacitor is given by (1-D)*Ts*ΔI (L1) / Cout.

Converter Waveforms

The voltage waveforms at both the input (upper trace) and output (lower trace) of the inductor L1 were measured while the difference waveform (middle trace) gives the voltage across the inductor. Figure 6 shows the converter operating in buck mode, while Figure 7 illustrates boost operation.

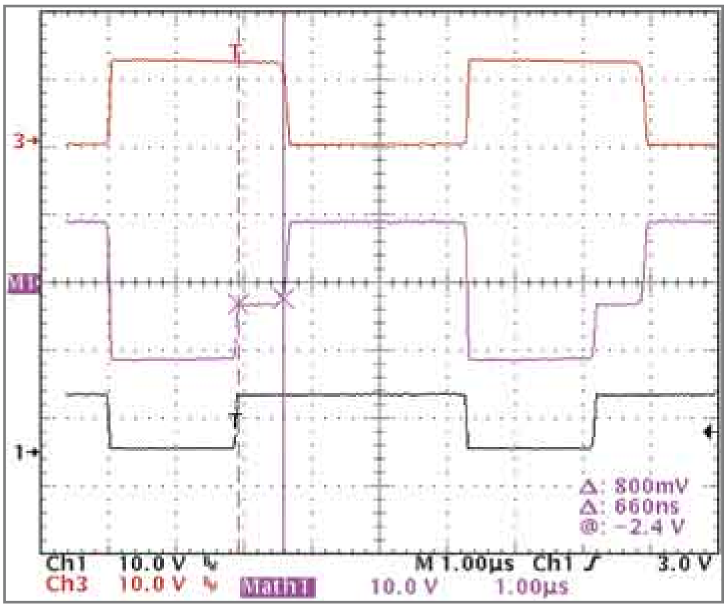

Figure 6: Waveforms in buck mode operation.

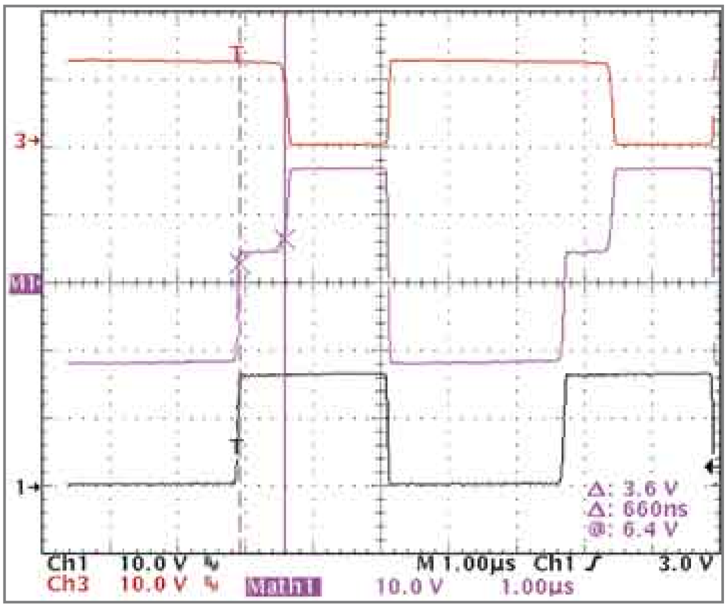

Figure 7: Waveforms in boost mode operation.

It is evident from Figures 6 and 7 that the inductor waveforms differ from a classic buck boost. The voltage across the inductor is clamped at (Vout–Vin) for the duration of the storage delay interval TD. During this interval Q2 is off and Q1 is on for its storage time. During this period, power is delivered to the output via Q1 and not by D1. Efficiency improvement is observed as the VCE(sat) of the PNP device (100mV) is less that the voltage drop across the Schottky diode D1 (300mV). If the time delay intervals were reversed and Q1 turned off first, power would cycle through the inductor L1, switch Q2 and diode D1. No power would be delivered to the load until Q2 turned off. The efficiency of the converter is shown in figure 8 and varied between 75% and 80%. The data was taken with Vin at 12V while the output was varied between 11 V and 26V at 700mA constant current load.

The V*µs balance expression given in equation 1 is modified as follows.

$$V_{in}\cdot D\cdot T_S \pm \left(V_{out}-V_{in}\right)\cdot T_D = V_{out}\left(1-D-T_D\right)\cdot T_S$$

Conclusions

ON Semiconductor's latest monolithic NCP3063 controller and family of e2PowerEdge ultra low saturation bipolar transistors can be combined to create a non inverting buck boost topology optimized to drive strings of LEDs at a constant current. A high side, low drop, current sensing scheme has been implemented, targeted for automotive, marine, and other high efficiency applications were the input voltage may be loosely regulated. The output from the current sense is used to vary the slope of the oscillator ramp and achieve duty cycle modulation, independent of the gated oscillator function provided by the IC. The classic transfer function of the buck boost converter is modified by the storage time interval between the NPN and PNP bipolar switches. ■

Simple and Accurate Constant Current Sensing for Non-Isolated LED Drivers

> John S. Lo Giudice, Application Engineer, STMicroelectronics

Many appliances and consumer electronics application are using LED lights that are driven by a non-isolated power supply. This circuit describes a novel approach to implement constant current control mechanism inexpensively and accurately.

Convention approaches of implementing current limit would not work in non-isolated buck converters because of floating reference for the control circuitry. In the circuit example shown below, a resistor and capacitor is used in the freewheeling diode path to capture the falling edge of inductor current. Since freewheeling circuit carries current for the majority of the duty cycle, this circuit provides reasonable accuracy. In addition, this circuit solves the issue of floating ground by referencing the control signal to same ground as the control circuitry.

A simple inexpensive Pulse Width modulation chip incorporated with a MOSFET is ideal for building a constant current driver for LEDs. In the circuit example shown below STMicroelectronics' VIPer22A was used to test this concept. This buck topology is usually used with constant voltage circuits by referencing the output voltage through a zener back to the feedback pin. Output current is senses during the freewheeling action. When the MOSFET is off, the current circulates through L2, the LEDs, D9 and R4. This period is longer than the on time of the MOSFET thus providing a reasonable accuracy. The current that is going through R4 is turned into a voltage and is stored and filtered by C4. When the MOSFET turns on again and D9 becomes back biased, the voltage that is stored in C4 rides on top of the source, which is the reference for the IC, biasing Q2 which regulates the proper voltage to the feedback pin 3.

The wide range of voltage for Vdd Pin, 9V to 38V, of this particular IC makes it ideal for this application, because the range of Vdd voltage is essentially the output voltage range. Hence this circuit can be used to drive 3 to 10 LEDs. If the LED string is not connected, the output voltage will climb to the over voltage level and lead the circuit into a hick up mode. D6 blocks the voltage during the freewheeling time and can be a general purpose diode.

Experimental results show that the circuit works well for a variable numbers of LEDs and can be even tighter for a fixed number. By changing the number of LEDs, the load regulation can be checked. The line regulation is also shown for a fixed number of LEDs from 90Vac to 264Vac. The results were measured on a board with the following results.

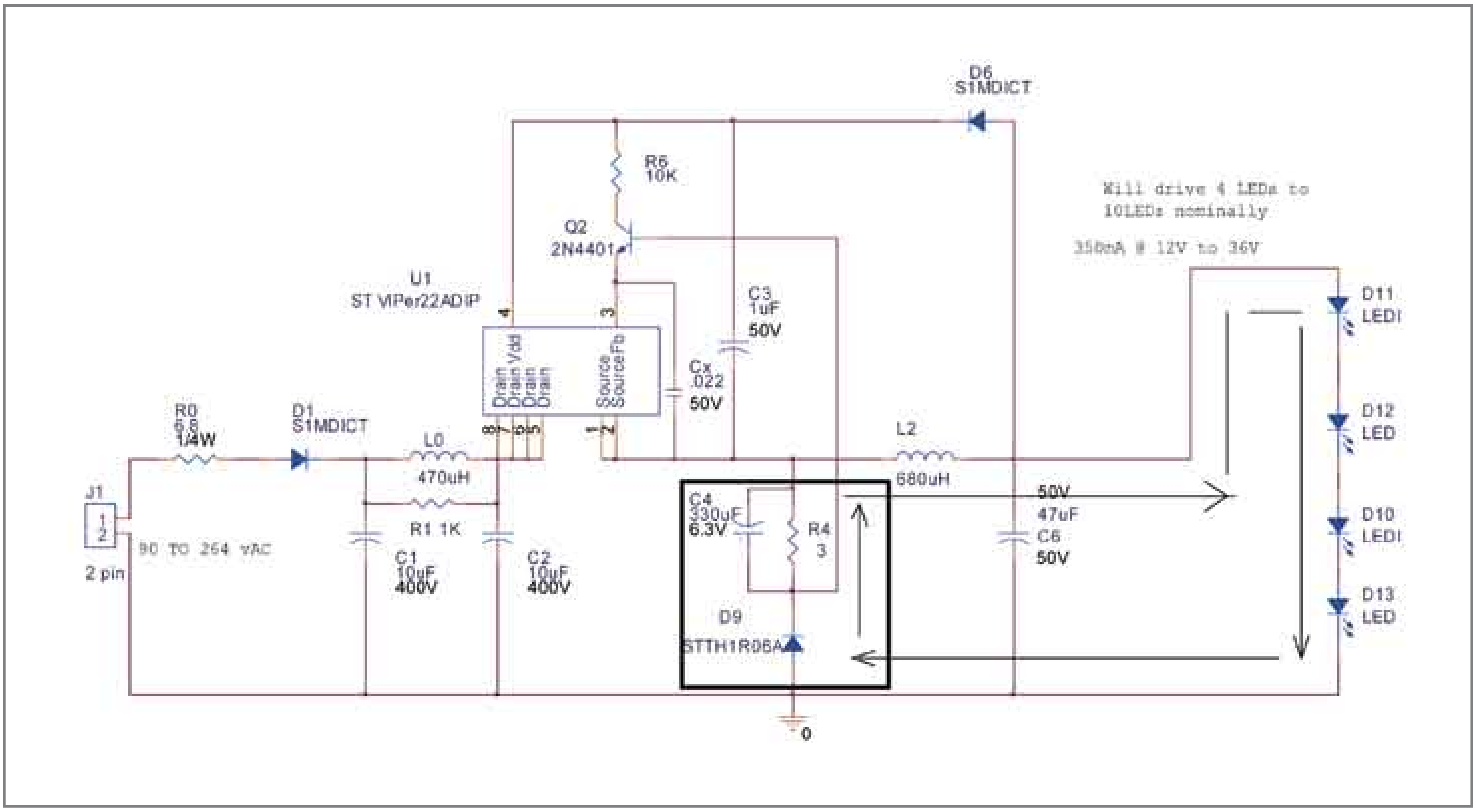

Figure 1. Schematic of circuit.

Since the current is triangular with a very large swing, C4 should be greater than 50 times the time constant. The higher the capacitance the better the regulation is. In this case 3Ω*330uF=9 ms which is much higher than the 17us period. Below is a scope picture of the current flowing through the inductor. The resistor turns the current into a voltage. The capacitor smooth out the peak voltage into an average voltage. That voltage is fed into the feed-back pin for regulation. The jump seen during the on time, which is represented by the rising of the current, is attributed to the common mode noise of the circuit because that point is flying from -1V to the peek of the input voltage.

The regulation is derived from measured results on a power supply board by varying the load from 3 to 10, 1Watt LEDs.

Load regulation		Line regulation	
LEDs	Current	Input	8 LEDs
3	362	90	350
4	358	115	329
5	352	132	326
6	344	180	329
7	336	230	336
8	328	264	340
9	321		
10	314		

Table 1: Load regulation, currents in mA (left), and Line regulation, voltages in V_{ac} (right).

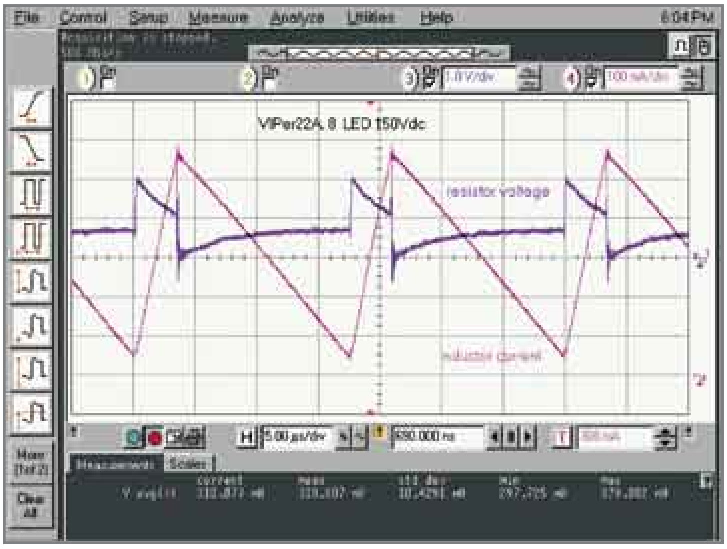

Figure 2: Inductor current and voltage for feedback.

The above plotted currents and voltages give the following graphs.

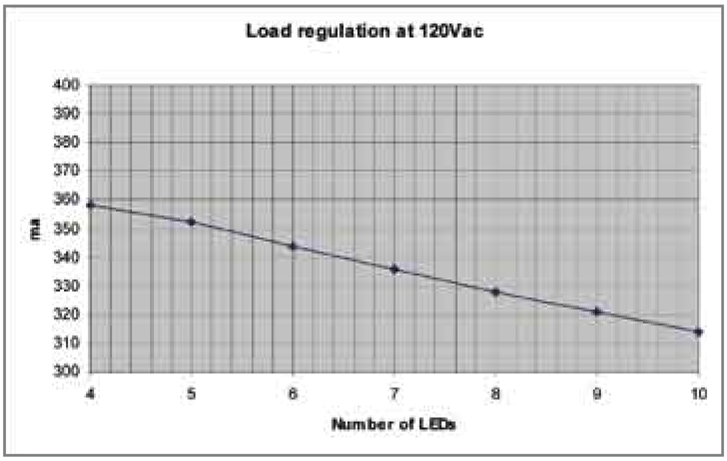

Figure 3: Load regulation.

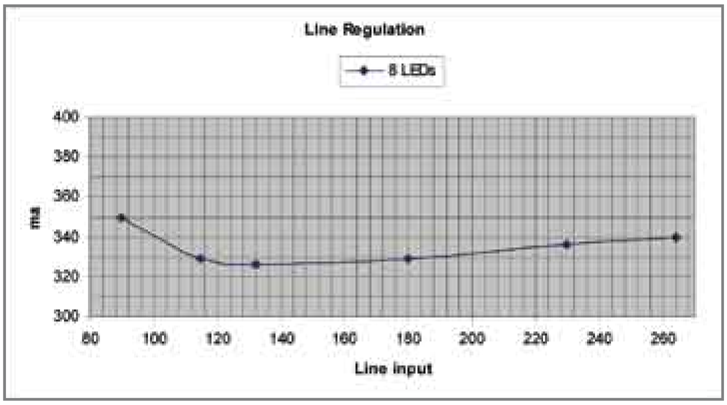

Figure 4: Line regulation.

This circuit delivers +/-6% load regulation from 4 to 10 LEDs and a line regulation of +/- 3.4% for 8 LEDs, when the line is varied from 90Vac to 264Vac.

Figure 5: Most recent driver board.

The actual board measures 55mm by 22mm making it compact for driving LEDs. ■

Reliability Test of LED Driven by PWM Technique

> B. J. Huang et al., Department of Mechanical Engineering, National Taiwan University

The solar-powered LED lighting system has been commercialized for a long time. The system usually consists of a DC to DC converter in order to convert the battery voltage into a fixed voltage or current for the LED lighting luminary. This will cause energy loss and system reliability due to the failure of DC/DC converter. In the present study, we develop a special technique to drive the LED luminary directly from battery utilizing PWM technique in order to remove the DC/DC converter. However, instantaneous current overdriven can occur easily due to the variation of battery voltage with the state-of-charge of battery.

In the present study, we setup a thermal chamber with temperature variation to within 40±3°C. A LED luminary

was specially designed for the LED reliability test with four different circuits with each circuit connecting three LED lamps serially. A driver is designed to provide 4 kinds of power inputs to LED: (a) 350mA constant current, (b) 700mA,100Hz, duty cycle=50%, (c)700mA, 10KHz duty cycle=50% and (d) 1050mA, 100Hz, duty cycle=33%. The tests were performed simultaneously to compare light decay between normal drive condition (a) and other PWM driving conditions (b, c, d). The accumulated total test time so far is more then 7,032 hours and has shown no significant light decay in 4 different loops. This reveals that the PWM technique directly driven by battery is feasible and is able to reduce energy loss of DC to DC converter in the solar lighting system.

Introduction

The stand-alone-solar-powered lighting system must be properly designed in photovoltaic power generation capacity Wp, battery capacity C, and the power consumption, for obtaining a proper Lost of Load Probability (LLP) to deal with rainy and cloudy days [1]. A good charge/discharge strategy is also needed for assuring the system reliability [2]. This kind of solar-powered lighting system usually is installed in remote area where the grid power can not reach. It can save the power transmission line cost and has been shown that the stand-alone solar lighting system utilizing Light Emitting Diode (LED) as the light source can save energy with reasonable payback time in remote area [3]. The reason for utilizing LED is that the LED can have long lifetime (about 50,000 hours when properly driven) and can be driven by direct current (DC) from battery. But there is a problem for driving the LED directly from the battery. The battery voltage will change at different state of charge and it may damage the LED. Therefore, the stand-alone solar LED lighting system usually consist a DC/DC converter to convert the battery voltage into the LED driving voltage [4]. The DC/DC converter may solve the problem of the voltage variation but it also increases the system cost and reduce the system reliability due to additional component.

The LED can be driven by PWM driving technique to maintain an average current through LED which is acceptable. The LED bulbs can resist high current stress [5] which means the LED can be driven directly from battery by utilizing PWM technique. The present study focuses on reliability of LED luminaire using direct PWM driving technique.

Reliability Test Design

The present study first setup a thermal chamber that is heated by two 100W tungsten lamps and uses two on/off

controllers to control the chamber temperature to within 40±3°C. Figure 1 shows the design of the LED reliability test that is driven by the direct PWM technique. A LED luminaire was specially designed for this LED reliability test with four different circuits and each circuit connecting three LED lamps serially.

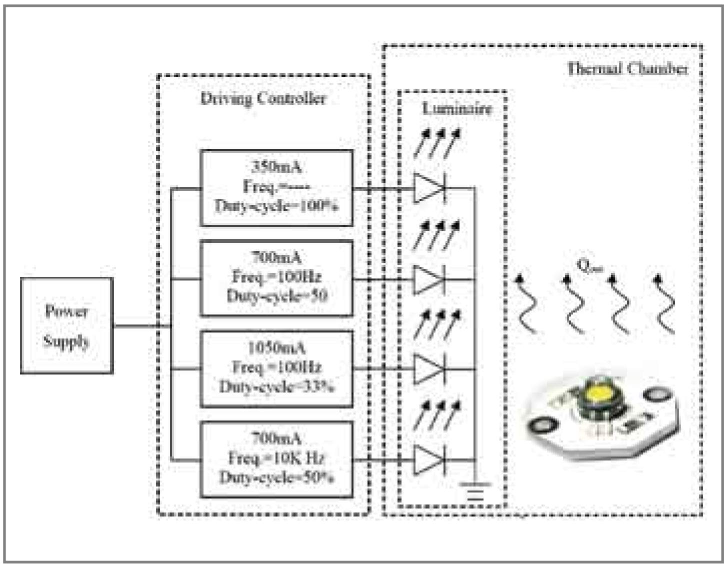

Figure 1: The design of the LED reliability test.

Special LED luminaire design

Figure 2 shows the aluminum PCB(Printed Circuit Board) and the special LED luminaire design. The aluminum PCB (74mm diameter) has 4 circuits (connecting 3 LEDs in series in each circuit). Each circuit was driven by different driver. A thermocouple was soldered on the middle of the aluminum PCB for measuring the temperature of the aluminum PCB. A heat conducting body was attached to the aluminum PCB to dissipate the heat of aluminum PCB. The LEDs were selected from the same product lot in a production line to reduce the variation of the thermal resistance in mass production. All LEDs were soldered on the aluminum PCB. Therefore, each LED on the aluminum PCB has the same junction temperature. Figure 3 shows the installation of a photo sensor (S2387) to measure the intensity of the light from LEDs.

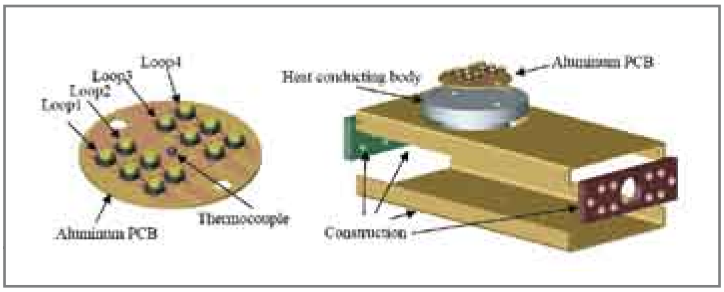

Figure 2: The Aluminum PCB and special luminaire design.

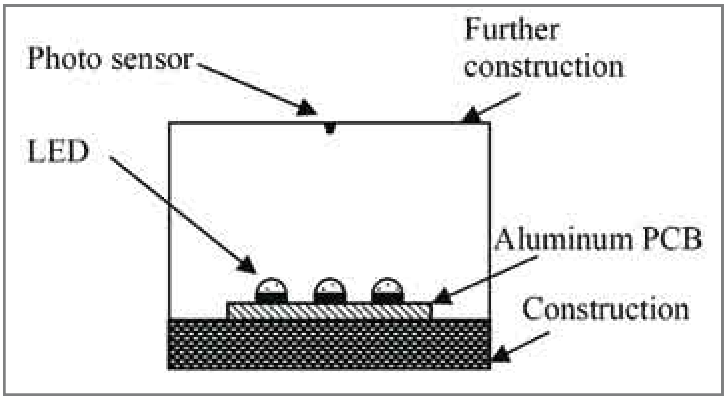

Figure 3: Installation design for photo sensor.

Thermal chamber

The size of the thermal chamber is 60x90x60 cm made by 3cm thickness styrofoam. The chamber was heated by two 100W tungsten lamps. There are two on/off controllers to control the chamber temperature. Figure 4 shows the design and the test arrangement of the thermal chamber. Two block boards were placed in front of the two 100W tungsten lamps for avoid heating the sensor of the on/off controller directly. Four thermocouples were placed at the same height and 10cm near the wall to measure the temperature distribution of the thermal chamber. Figure 5 shows the test result at four locations. The result shows that the thermal chamber can control the chamber temperature to within 40±3°C.

PWM driver and controller design

A LED driver is designed to provide 4 kinds of power inputs to LED: (a) 350mA constant current, (b) 700mA, 100Hz, duty cycle=50%, (c)700mA, 10kHz duty cycle=50% and (d) 1050mA, 100Hz, duty cycle=33%. The tests were performed simultaneously to compare different light decay between normal drive condition (a) and other PWM drive condition (b, c, d).

The LED luminaire is put in the thermal chamber to accelerate the light decay of the LED by increasing the ambient temperature. The power supply can provide a DC input to the driving controller then the driving controller can generate 4 different driving current which are list below to drive the LED.

(a)350mA constant current:
It is the most common way to drive the LED. This is the baseline of the LED lifetime.

(b)700mA, Duty-Cycle=50%, PWM-Frequency=100Hz:
In Case (b), the average current equal to 350mA but the current stress through the LED is two times greater then Case (a).

(c)700mA, Duty-Cycle=50%, PWM-Frequency=10kHz:
The average current equal to 350mA but the current through the LED is two times greater then Case (a) condition and the PWM-Frequency is 100 times greater then (b). This test intends to see the effect of frequency and the pulse stress.

(d)1050mA, Duty-Cycle=33%, PWM-Frequency=100Hz:
The average current equals to 350mA but the current through the LED is three times greater then Case (a).

Besides, a controller was designed using microprocessor to control the on/off for the different circuits of LEDs and measure the output of the photo sensor.

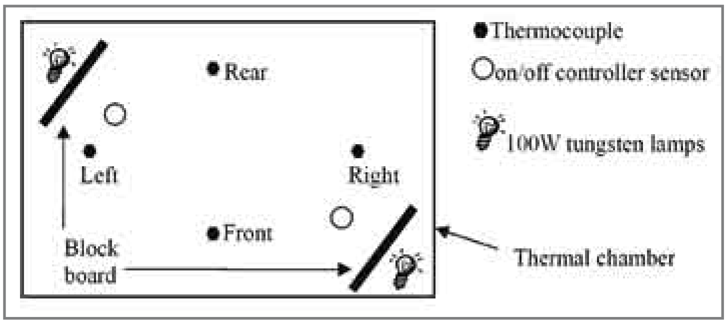

Figure 4: Thermal chamber design and test arrangement.

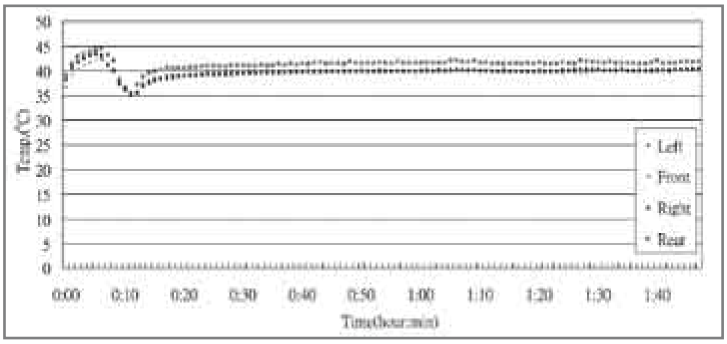

Figure 5: The test of the thermal chamber.

Test Results

Figure 6 shows the accumulated total test time so far is more then 7,032 hours and has shown no significant light decay in 4 different circuits. The aluminum PCB temperature shown in Figure 6 remains in 55±3°C.

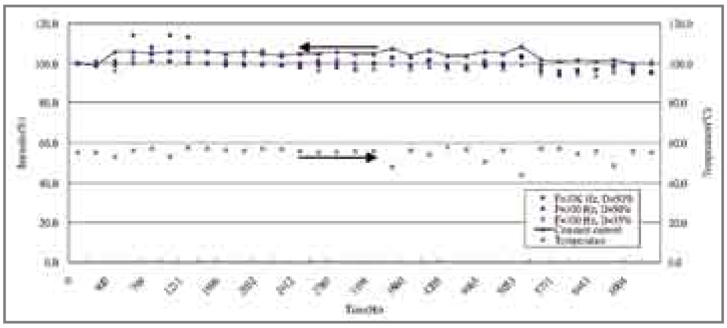

Figure 6: LED reliability test result.

Conclusion

The solar-powered LED lighting system usually consists of a DC to DC converter in order to convert the battery voltage into a fixed voltage or current for the LED luminaire input. This will cause energy loss and system reliability problem due to the failure of DC/DC converter.

In the present study, we drive the LED luminaire directly from battery utilizing PWM technique to remove the DC/DC converter. However, instantaneous current overdriven can occur easily due to the variation of battery voltage with the state-of-charge of battery. A LED luminaire was specially designed for the LED reliability test with four different circuits with each circuit connecting three LED lamps serially. A driver is designed to provide 4 kinds of power inputs to LED: (a) 350mA constant current, (b) 700mA, 100Hz, duty cycle=50%, (c)700mA, 10kHz duty cycle=50% and (d) 1050mA, 100Hz, duty cycle=33%. The tests were performed simultaneously to compare light decay between normal drive condition (a) and other PWM driving conditions (b, c, d). The accumulated total test time so far is more then 7,032 hours and has shown no significant light decay in 4 different loops. This reveals that the PWM technique directly driven by battery is feasible and is able to reduce energy loss of DC to DC converter in the solar lighting system. ■

Acknowledgement:

The present study was supported by Energy Bureau, Ministry of Economic Affairs, Taiwan.

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