CALIFORNIA
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Energy Research and Development Division

FINAL PROJECT REPORT

Ultra-Thin Flexible LED Lighting Panels

A New Technology Platform for Making Wide-Area LED Luminaires

June 2023 | CEC-500-2023-045

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Ultra-Thin Flexible LED Lighting Panels: A New Technology Platform for Making Wide-Area LED Luminaires is the final report for the project name EPC-18-003 conducted by Lucent Optics. The information from this project contributes to the Energy Research and Development Division's EPIC Program. For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at ERDD@energy.ca.gov.

ABSTRACT

Linear fluorescent lighting fixtures, such as recessed or surface-mount troffers and suspended architectural lights, are among the most common lighting fixtures in commercial spaces, with about 1 billion installed in the United States. These fixtures also represent one of the largest opportunities for energy saving in commercial buildings. While Light-emitting diode (LED) sources are widely recognized as being much more efficient, the adoption of LEDs in linear lighting systems has been slowed by the relatively high cost of LED products and the lack of sufficiently compelling visual differentiation from the incumbent fluorescent fixtures.

In this project, Lucent Optics developed a new platform technology (CoreGLO™) for making aesthetically appealing wide-area LED lighting luminaires at a fraction of the cost of traditional fluorescent and LED fixtures. The CoreGLO technology overcomes the design limitations of traditional lighting luminaires by providing sheet-like and flexible forms. It also provides lighting system developers with new design options such as curved shapes, transparency, and ultra-thin form factors. CoreGLO panels utilizes extremely small amounts of raw materials for distributing light with industry-leading efficiency and without glare. Such panels can be incorporated into various types of traditional lighting systems and will also enable creating new luminaire designs of various innovative forms and shapes. Independent performance tests of the developed prototypes demonstrated a luminaire-level efficacy of more than 120 lumens per Watt, which set a new efficiency record for large-area, thin-sheet lighting sources.

Keywords: light emitting diodes (LEDs), linear lighting fixtures, energy efficiency in buildings

Please use the following citation for this report:

Vasylyev, Sergiy and Nick Masalitin. 2023. Title of Report Ultra-Thin Flexible LED Lighting Panels. A New Technology Platform For Making Wide-Area LED Luminaires. California Energy Commission. Publication Number: CEC-500-2023-045.

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Introduction

California has set an ambitious goal to double energy savings in existing buildings by 2030. Interior lighting accounts for almost a third of commercial electricity usage, at about 300 billion kWh, and represents a significant energy saving opportunity by replacing outdated and inefficient technologies used for space illumination.

Linear fluorescent lighting fixtures employing fluorescent tubes currently dominate the commercial buildings landscape. These fixtures have become extremely popular due to their ability to emit massive amounts of light with less glare compared to other types of lights. Lighting products in this category particularly include 1′ by 4′, 2′ by 2′ or 2′ by 4′ recessed and surface-mount troffers as well as suspended and architectural lights. Linear fluorescent lights can be found in more than 90 percent of commercial buildings, with about 1 billion installed in the U.S.

However, linear fluorescent fixtures have a relatively poor efficiency and significantly contribute to the carbon footprint of buildings. The fluorescent technology is also commonly associated with poor light quality, flicker, and the need of periodic tube replacement. In addition, fluorescent tubes contain mercury and can be a source of environmental poisoning when improperly disposed and recycled.

Light-emitting diode (LED) technology is much more energy efficient, environmentally friendly, and long-lasting than fluorescent tubes. Therefore, replacing the outdated florescent fixtures with LED fixtures has an enormous potential for energy savings, reducing CO_2 emissions and overall improving the sustainability of building operations.

However, the widespread adoption of LEDs in linear fixtures is facing several challenges. The relatively high cost of replacement LED fixtures makes it difficult for the building owners to justify the transition to the LED technology for the energy savings reasons alone. Furthermore, most linear LED lighting fixtures carry the same overall appearance as the fluorescent fixtures they are intended to replace. This lack of favorable visual differentiation compared to the incumbent fluorescent technology even further discourages the consumer since the expectations from transitioning to a new technology often implies improved aesthetics.

Diffuse LED sources with very thin and flexible sheet forms could help overcome these challenges. They could improve the material efficiency, reduce the cost, enable new design opportunities, simplify installation via drop-in whole-fixture replacement, and further enhance the efficacy and light quality at the luminaire level. If such light sources could be made inexpensively and provide the wall-plug efficiency comparable to conventional LED luminaires, they could dramatically expedite the adoption of energy-efficient LEDs in general lighting and unlock massive new opportunities for energy savings.

Project Purpose

Prior to this project, there were no commercially available LED lighting products with thin and flexible sheet forms. Moreover, there was no commercially viable technology for making such LED products with qualities suitable for general lighting applications.

This project developed a platform technology for making diffuse LED panels with thin and flexible forms that would help create new design opportunities for general illumination, set a new efficiency benchmark for such panels, and establish a pathway for lowering the cost of ownership of linear LED lighting fixtures. The project focused on solving the problem of a relatively low adoption rate of LED technology, developing a lowest cost solution for drop-in replacement of standard-size fluorescent fixtures (for example 2′x2′, 1′x4′, and 2′x4′ troffers), and enabling a variety of new design options, forms and designs for lighting, including curved, transparent and free-form shapes.

Project Approach

The Lucent Optics, Inc. project team made low-cost LED lighting panels that are very thin and flexible. They achieved this by using high-performance inorganic LEDs along with a thin sheet of optical plastic. The project team focused on developing key elements of this concept and integrating the system and testing the developed technical solution.

The team created LED modules that can be used with ultra-thin and flexible lighting panels. These panels can be made in sizes that are commonly used for commercial fluorescent lights. To distribute the light emitted by the LED modules over a wider area, the team developed thin and flexible plastic materials called optical waveguides. They also came up with a way to pattern these plastic materials efficiently to maximize the brightness of the light and ensure it is evenly distributed. Finally, they developed optical couplers that minimize the loss of light when connecting high-brightness LEDs to thin and flexible waveguides.

To complete this work, the project team designed and fabricated commercial-size, fully functional ultra-thin and flexible LED lighting panel prototypes and assessed their performance and addressed system-level optimization, electrical, thermal management, structural and installation issues.

Project Results

The project achieved the technical objectives and successfully developed a new platform technology for making high-performance diffuse LED panels with thin and flexible forms. The project team built and tested several operational prototypes of ultra-thin LED lighting panels and manufactured several demonstrational prototypes of lighting fixtures employing such panels.

The lighting fixture prototypes demonstrated new opportunities for lighting design, particularly including large-area, glare-free LED lighting sheets, curved shapes, transparent appearance, and custom patterns of the emission. The prototypes also demonstrated a clear pathway for lowering the intake of raw materials, manufacturing cost, and embodied energy in general illumination systems. It was also demonstrated that the developed technology can be used as a low-cost alternative to traditional LED lighting fixtures for replacing linear fluorescent fixtures in commercial space.

The test results confirmed that the performance of the thin and flexible panels are above the average standards within the respective classes of illumination systems. A new world record for the size of diffuse thin-sheet lighting panels has been established and a new efficiency benchmark has been set for such panels at 122 lumens/Watt. This represents more than 70 percent improvement compared to traditional fluorescent fixtures that are popular in office buildings, for example.

Technology and Knowledge Transfer. Advancing the Research to Market.

During this project, the team delivered a number of presentations and live technology demonstrations at scientific and technical conferences, illumination industry workshops, and clean energy technology showcases, with a broad participation of scientific community, industry experts and lighting industry stakeholders. Two of these conferences were the Clean Energy Technology Showcase, October 2019, Sacramento, California, and the US Department of Energy, SSL R&D Workshop, January 2020, San Diego, California.

Lucent Optics has established pilot manufacturing of the key components of the ultra-thin and flexible LED lighting panels and commenced commercial production of such components and certain types of the fully integrated illumination products based on the developed technology. Lucent Optics' pilot commercial lighting panel was selected by the Illuminating Engineering Society for inclusion in the 2021 IES Progress Report which recognizes significant new advancements in lighting products, research, publications, and design tools for its annual report.

Benefits to California

To help achieve its greenhouse gas reduction and energy efficiency goals, California requires a comprehensive technology solution to the problem of reducing the energy consumption by illumination systems in commercial buildings. This project has developed a new technology platform for making high-performance, aesthetically pleasing LED lighting systems at a low cost and using extremely small amounts of raw materials. A broad use of this technology platform in the lighting industry could expedite the transition from an outdated fluorescent tube technology to the more energy efficient and environmentally friendly LED technology without the relatively high price tag associated with the traditional LED lighting systems, while saving 50 percent to 70 percent of the cost used for illuminating building interiors. The developed technology also promotes using sustainable practices in making illumination systems by introducing additive manufacturing and the principles of reduced material intensity into the production process. A further development and commercialization of this technology could also bring significant manufacturing employment opportunities to California, potentially adding of thousands of jobs spread over several sectors such as lighting fixture assembly and related supply chain, installations, design, engineering, and sales, distributions and logistics.

CHAPTER 1: Introduction

Background

California has set an ambitious goal to double energy savings in existing buildings by 2030. Interior lighting accounts for about 30 percent of commercial electricity usage and consumes about 26,000 GWh per year (CEC, 2012), representing a significant energy saving opportunity by replacing outdated and inefficient technologies used for space illumination.

Linear fluorescent lighting fixtures, such as 1′ by 4′, 2′ by 2′ or 2′ by 4′ recessed and surface-mount troffers as well as suspended and architectural lights, are the most common lighting fixtures in commercial spaces. Linear luminaires have become extremely popular due to their ability to emit massive amounts of light with less glare compared to other types of fixtures.

However, most of the existing linear luminaires employ fluorescent tubes which are commonly associated with subpar efficiency, poor light quality, flicker, and the need of periodic tube replacement and discarding. There are hundreds of thousands of commercial buildings in California which interior is illuminated by linear lighting fixtures employing T12, T8, and T5 tubular fluorescent lamps. It is estimated that California buildings contain more than 170 million of fluorescent tubes (PG&E, 2017), with a total 1 billion installed base of linear fluorescent lights in the U.S.

Besides wasting energy and significantly contributing to the carbon footprint of buildings, fluorescent tubes contain mercury and can be a source of environmental poisoning when improperly disposed and recycled. The fluorescent tubes also require periodic replacement which requires additional freight transportation and/or trips to a store which contribute to air pollution on their own.

LEDs are now considered a preferred type of light source for general illumination since they are twice as efficient as fluorescent tubes and 5-10 times more efficient than incandescent lamps. LED luminaires are typically more environmentally friendly, long-lasting and can be 40 percent to 70 percent more energy efficient than fluorescents, depending on the implementation of the end-product. Therefore, replacing the outdated florescent fixtures with LED fixtures has an enormous potential for energy savings, reducing CO_2 emissions and overall improving the sustainability of building operations. It is estimated that the linear fluorescent fixtures represent the largest potential for energy saving among all types of lighting products (Penning, 2017). On the energy aspect alone, if all the existing linear lighting fixtures in the U.S. were to be replaced with LED luminaires, it could save up to 70 TWh of site electricity, or more than 650 tBtu of source energy.

However, despite the use of LED products in the linear fixture application near doubling in the last few years to 20 percent penetration, fluorescent lamps still dominate the commercial lighting market. A more widespread adoption of LEDs in linear fixtures is facing several challenges. One challenge is a relatively high cost of replacement LED fixtures. Considering that the replacement fluorescent tubes are fairly cheap, this makes it hard for building owners to justify the replacement for the energy saving reasons alone. Another challenge is more of a design nature. LEDs are very compact and extremely bright light sources that tend to create hot spots unless they are completely hidden from view and their light emission is thoroughly diffused. As a result, the current approaches used for making LED luminaires often leads to bulky luminaire designs that resemble the fluorescent luminaires they are intended to replace. This lack of favorable visual differentiation from the incumbent technology even further disincentivizes potential customers and creates an additional barrier for a broader adoption of LED lighting in commercial buildings.

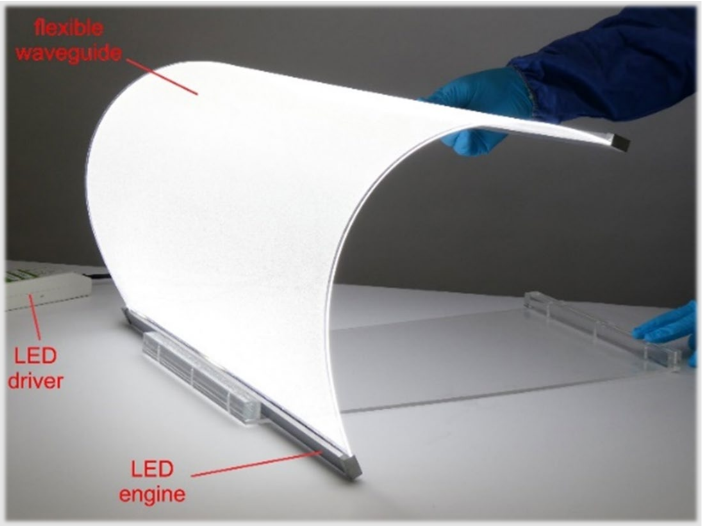
Thin and flexible LED sources could help overcome these challenges by improving the material efficiency, reducing the cost, enabling new design opportunities, and further enhancing the efficacy and light quality at the luminaire level. If such light sources could be made inexpensively and provide the wall-plug efficiency comparable to conventional LED luminaires, they could dramatically expedite the adoption of energy-efficient LEDs in general lighting and unlock massive new opportunities for energy savings.

CoreGLO™ Technology

Lucent Optics previously proposed and demonstrated the concept of a low-cost LED lighting panel with ultra-thin and flexible form factor and produced some of the world's first bendable sheet-form LED lighting products with highly uniform emission. A particular implementation of this concept, called CoreGLO™, uses high-performance inorganic LEDs in combination with a thin optical plastic sheet.

The CoreGLO technology leverages the high efficacy and reliability of mature LED technology and enables manufacturing high-performance linear luminaires at a lower cost and using much less raw materials compared to traditional approaches. The LEDs are incorporated into a bar-shaped, passively cooled LED engine which is used to illuminate the plastic sheet from an edge. The plastic sheet operates as an optical waveguide redistributing the LED light and creating a uniform glow from the entire surface of the panel (Figure 1).

Figure 1: 2'x2' Thin and Flexible CoreGLO Panel



Source: Lucent Optics, Inc.

The CoreGLO panels, if fully developed and commercialized, may help solve the problem of relatively high cost of LED fixtures by providing a relatively simple sheet-form lighting structure and using very small amounts of parts and raw materials compared to the traditional lighting systems which often which use complex and material-intensive structures and optics. The plastic sheet utilized for the waveguide also forms the main structural body of the panel and essentially eliminates the need of bulky luminaire structures to uniformly spread the light and hide the individual LEDs from viewing. Lucent Optics sources such plastic sheets as a commodity and then processes them into waveguides using an inexpensive patterning process which allows for reducing the panel cost even further. The ultra-thin form factor of the panel also leads to its low weight and helps with its transporting and installation. CoreGLO panels having the industry's lowest weight per unit area of only 2 kg/m^2 have been demonstrated.

The CoreGLO technology also creates new opportunities for domestic manufacturing with sustainable production and extremely low embodied energy. The manufacturing technology currently considered for making CoreGLO panels features a minimum use of electricity and water, uses no virtually harsh chemicals, and avoids any harmful manufacturing-related pollution.

The thin and flexible form factor of CoreGLO panels may also additionally contribute to lowering the barriers to a broader LED technology adoption by opening new opportunities for lighting design, overcoming some design limitations of traditional lighting luminaires, and significantly expanding the ways in which lighting can be integrated into the building interior. Each CoreGLO panel is essentially a wide-area solid-state light source with uniform, glare-free emission. This light source can be used as stand-alone luminaire or incorporated into lighting fixtures in either planar or curved configurations. New lighting designs can be created not only by bending the panels but also by customizing their overall appearance, including transparency and different emission patterns, and by incorporating them into various surfaces of the building interior or covering large areas such as walls, ceilings, and even windows.

CHAPTER 2:
Project Approach

Project Objective and Scope

The objective of this project was to create a universal, area-distributed LED source and associated technology platform that would create new design opportunities for general illumination through introducing thin and flexible forms for the light sources, set a new efficiency benchmark for large-area sheet-form luminaires using such light sources, and lower the cost of ownership of wide-area lighting luminaires. The project particularly focused on solving the problem of a relatively low replacement rate of linear fluorescent fixtures with LED technology, developing a lowest cost solution for drop-in replacement of standard-size fluorescent luminaires (for example 2′x2′, 1′x4′, and 2′x4′ troffers), and enabling a variety of new design options, forms and designs for lighting, including curved, transparent and free-form shapes.

Performance Targets

The overall long-term cost and performance targets for the wide-area, ultra-thin and flexible LED panels are compared to targets achieved during this project in Table 1.

Table 1: Cost & Performance Targets

Metric	Performance Target (long-term)	Achieved	Notes
System Cost ($/klm)	$20/klm when in full-scale production	<$35/klm	At pilot-scale production
Luminaire-level efficacy (lm/W)	120-160 lm/W	117-122 lm/W	depending on panel size and configuration
Surface luminance (cd/m^2)	<1,000 cd/m^2 and up to 20,000 cd/m^2	<1,000 cd/m^2 and up to 12,000 cd/m^2	depending on panel size and configuration
Surface emission uniformity (%)	>85%	>85%	
Panel sizes	Up to 2ft x 4ft, optionally up to 4ft x 4ft	Up to 2ft x 4ft	customizable to other dimensions up to the maximum size
Panel thickness range (mm)	0.5mm to 2mm	1.2mm to 2mm	depending on panel size and configuration

Weight (lbs)	<0.5 lbs/ft^2	0.5 lbs/ft^2	without the LED driver
Flexibility/bend radius (mm)	down to 30mm (at the lower end of the targeted thickness range)	<100mm	at 1.2mm thickness
Design options	opaque with one-sided or two-sided light output (for example for direct/indirect illumination), transparent, diffuse (lambertian) or directional (such as bat-wing) emission	1) opaque with one-sided light output and diffuse emission 2) transparent with two-sided light output and diffuse emission on both sides	
Color rendering index (CRI)	Ra>90	Ra>90	lower-CRI options are also available

Source: Lucent Optics, Inc.

The project was structured to support achieving at least some of the above targets and make a significant progress towards achieving the other targets.

Overview of Project Technical Tasks

The following technical tasks were planned for the project:

LED Module Development

The goal of this task was to develop high-performance integrated LED strip modules that are optimally designed for the ultra-thin and flexible LED lighting panel and that could provide sufficient light output for making flexible lighting panels in sizes typical for commercial fluorescent troffers.

Since the LED module is a major component of the CoreGLO panel which determines the light output and sets a number of constraints on the other components, meeting this goal required enhancing the overall design of sheet-form LED sources.

Flexible Light Guiding Substrate Development

This task was focused on developing thin and flexible plastic substrates suitable for distributing light emitted from the LED strips over wide area panels and creating a distributed surface-emitting light source.

Substrate Patterning For Light Extraction

The focus of this task was to develop an efficient and robust patterning technique for the flexible plastic substrates to maximize the light extraction efficiency and achieve light emitting surface brightness uniformity and light extraction efficiency above the average standard.

Light Coupling Optics Development

This task was aimed at developing optical couplers that could minimize optical losses for coupling high-brightness LEDs to thin and flexible light guiding substrates which thickness is less than the size of the respective LED packages.

System Integration

The goal of this task was to design and fabricate commercial-size, fully functional ultra-thin and flexible LED lighting panel prototypes as well as assess their performance, addressing system-level optimization, electrical, thermal management, structural and installation issues. A particular focus was on demonstrating ultra-thin, flexible LED lighting panels that could be used for replacing some of the most prevalent types of linear fluorescent light fixtures, at custom and standard sizes, and surface-mount troffers.

CHAPTER 3:
Evaluation of LED Lighting Design Factors

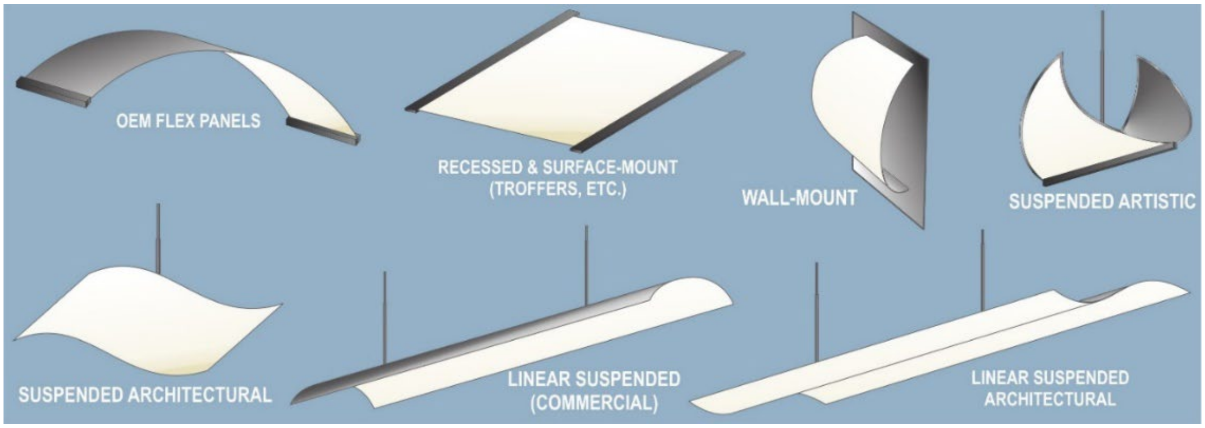
General Design Considerations

In developing CoreGLO as a platform technology, the project team has targeted several types of lighting luminaires that can benefit from uniformly emitting light from a large area. In general lighting applications that are aimed to provide a uniform level of illumination throughout an area, suitable examples of conventional luminaires that can be replaced or augmented with CoreGLO panels include recessed and surface-mount linear fixtures, such as 2′x2′, 1′x4′ and 2′x4′ fluorescent troffers or their LED-based equivalents. Further examples include linear suspended lights (pendants), including those used for general lighting or architectural and decorative purposes.

However, the CoreGLO technology was also not meant to be not limited to linear-type fixtures. Additional targeted applications include wall lighting (for example sconces), artistic fixtures, and sheet-form light emitting panels that can be hung from the ceiling or integrated into various surfaces of building interior (such as walls, ceiling, partitions), including simple rectilinear or curvilinear forms (Figure 2).

In view of the broad range of the targeted lighting designs, each having its unique requirements and constraints, application-specific implementations of the CoreGLO panels are expected to differ significantly from one product to another. Furthermore, a CoreGLO panels can be configured as a complete luminaire or as a light-emitting component (light source) of a larger lighting fixture which can its own specific design. Therefore, in developing the overall structure of the panel, the team focused on identifying its preferred design parameters which could apply to most types of products with the emphasis on general lighting applications.

Figure 2: Illustrative Luminaire Types and Designs Targeted by the CoreGLO Technology



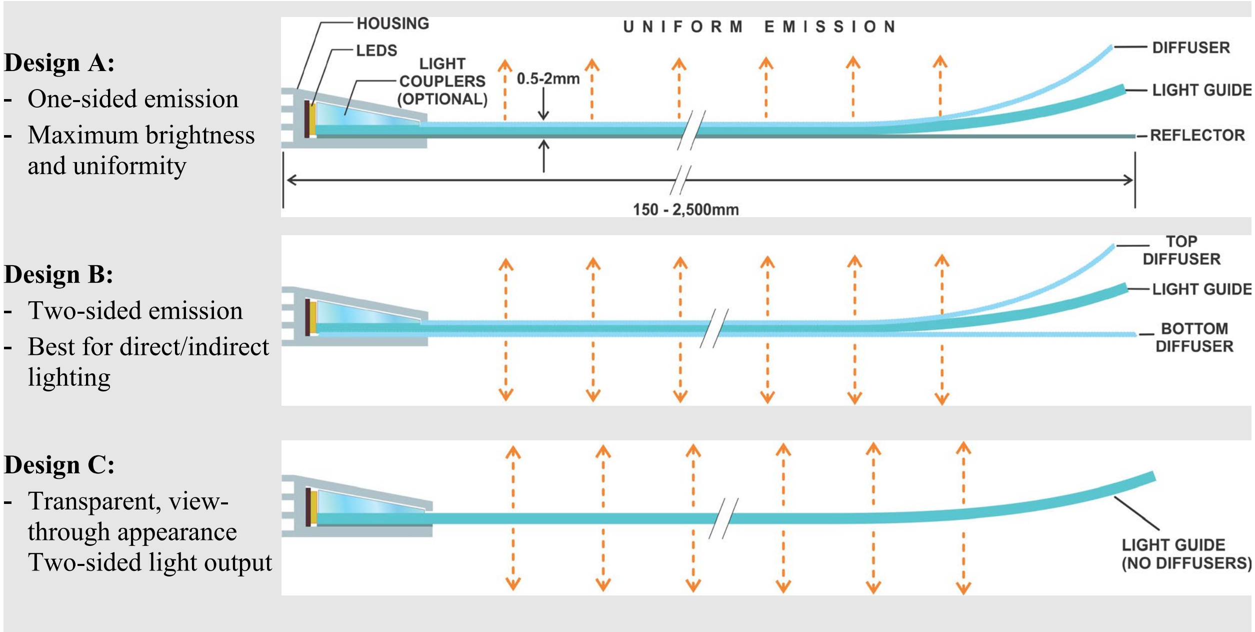
Source: Lucent Optics, Inc.

Overall Construction and Materials

The CoreGLO panels further developed in this project share some of the design characteristics of conventional edge-lit illumination panels but take the basic edge-lit design to a next level by implementing several enhancements that are not found in the incumbent edge-lit designs. These enhancements particularly include a significant reduction of the intake of raw materials, improving luminaire-level efficacy, providing new design options such as thin and flexible forms, enhanced angular control of the emission and highly customizable appearance. The customization may include, for example, transparency and various types of surface patterning.

A basic CoreGLO panel includes a thin and flexible light guiding sheet made from a high-transparency plastic and a linear LED module illuminating the light guiding sheet from an edge. Depending on the end-product requirements, the panel can be designed in three different configurations (Figure 3). In particular, it can be configured for one-sided emission with highly homogeneous surface brightness (Design A), two-sided emission with a prescribed up/down distribution (Design B), or for two-sided emission and transparent appearance (Design C).

Figure 3: Principal Variations the Optical Configuration of CoreGLO Panels



Variations depend on design choices regarding the direction of the emission and transparent/opaque appearance of the target lighting luminaire.

Source: Lucent Optics, Inc.

The light guiding sheet has a special pattern designed to redistribute the LED light over its entire area and re-emit that light from the sheet surface in the form of a soft, highly uniform glow. The LED module employs a series of mid-power, high-brightness LEDs which is normally encased within a linear structural housing in a finished luminaire. The module is permanently attached to the edge such that the CoreGLO panel forms a frameless, flexible sheet-form structure. Additional linear LED module(s) can be attached to the opposite edge to increase the light output. In a basic configuration, the CoreGLO panel has the appearance of and can be handled similarly to a raw plastic sheet having structurally reinforced edges. This sheet-form panel can replace the bulky structures of traditional lighting luminaires of the same area, generally without sacrificing the overall light output and installation options.

The panel is powered by a low-voltage DC power supply which is normally detached from the panel and can be mounted separately from the luminaire. However, for certain space-conscious applications, the power supply can also be integrated into the LED module similarly to tubular LED lamps.

For the cases when the lowest thickness and maximum flexibility are desired, the CoreGLO panel may include special optical couplers that are used for enhancing the optical coupling of LEDs to the edges of the light guiding sheet. The couplers can help reduce the optical losses associated with the lower thickness of the light guide compared to the size of the LEDs and also mask the intensity and color variations among individual LEDs, thus reducing the requirements to LED manufacturing and binning. A low-profile structural housing encloses the LEDs and enhances heat dissipation.

A short list of optical-grade polymeric materials can be technically considered as appropriate solutions for making the light guiding sheet and optional diffuser films. However, when cost and optical performance are taken into consideration, acrylic (polymethyl methacrylate, PMMA) can be an optimal option for the light guiding sheet while acrylic or polycarbonate materials can be used for the diffuser parts, when applicable.

Physical Characteristics

The target size range of CoreGLO panels is mostly determined by the types and sizes of wide-area lighting luminaires in which the panels are going to be used. Considering the wide variety of sizes and of conventional lighting fixtures, Lucent Optics is planning to make CoreGLO panels available in several standard rectangular shapes and sizes ranging from 12″x12″ to 2′x4′ (such as in 6″ or 12″ increments in each dimension) and also offer custom sizes, shapes and form factors, including oversized dimensions.

The weight and cost of a lighting fixture generally tends to increase roughly proportionally to the size of its light emitting area. Therefore, minimizing the intake of raw materials per unit area is especially important for luminaires that span from about one foot to several feet across. For these types of luminaires, it was determined that the thickness of the panel (across its light emitting area) of about 2 mm or less would provide sufficiently high-cost savings compared to the traditional designs to stimulate a broader market adoption of the technology. Furthermore, a 2-mm thickness marks a relatively fuzzy threshold between “flexible” and “rigid” structures when it comes to handling sheet-form panels made from plastic materials. On the other hand, while CoreGLO panels have been demonstrated at thicknesses of 0.5 mm and even less, various considerations related to maintaining the structural strength and ease of handling and installation put some practical limits on the lower end of the panel thickness range, especially for relatively large panels.

In view of these and other design considerations, the project team established an optimal range for the thickness of CoreGLO panels of 1-2mm for general lighting applications and for some types of specialty lighting fixtures. At those thicknesses, it was determined that CoreGLO panels can be made highly flexible and could support bend radii down to 10-20cm range without building excessive internal stresses that could cause panel breakage. This level of panel flexibility is believed to satisfy most of the demand for thin and flexible forms in lighting luminaires.

The target weight of the complete CoreGLO panel is less than 1 lbs/ft^2, with some configurations targeted at even lower weight or less than 0.5 lbs/ft^2, depending on the design options, which would be the industry's lowest weight among all types of lighting luminaires. At this ultra-lightweight sheet-form configuration, these panels are expected to significantly reduce the manufacturing and shipping expenses and simplify installation and integration of CoreGLO products into building interiors.

Efficacy

The luminaire-level efficacy, which represents the luminaire light output divided by luminaire input power and expressed in lumens per watt (lm/W), is of a critical importance for general lighting. The commercial markets are still dominated by linear fluorescent troffers employing fluorescent tubes. Most fluorescent troffers have luminaire-level efficacies of around 65-70 lm/W. The LED replacement troffers have efficacies in the range from 90 lm/W to 120 lm/W, on average, with a relatively small number of top performers reaching or exceeding 130 lm/W (U.S. DOE, 2018). The Design Light Consortium (DLC)[1] defines minimum efficacy values of 100 lm/W and 125 lm/W for DLC Standard and Premium troffers, respectively.

Accordingly, at least for the direct replacement and retrofits of fluorescent troffers, the CoreGLO panels should preferably have luminaire efficacies greater than 100 lm/W while maintaining the thin and flexible forms to be competitive in this market segment. Efficacies of 125 lm/W or more would be needed to qualify for DLC Premium product designation and position CoreGLO panels among top-performing luminaires in the linear troffer category.

Several prototypes of thin and flexible CoreGLO panels have demonstrated luminaire-level efficacies above 100 lm/W with earlier-generation commercially available LED packages. An effort is underway to exceed 120 lm/W in the near term and reach up to 160 lm/W in a longer term through further design and manufacturing technique optimization and careful selection of CoreGLO components and materials.

However, it should be noted that the previously discussed high-efficacy requirements mostly apply to the cases when either the value of thin and flexible forms of CoreGLO panels is not of a significant importance in a particular luminaire design and when the cost advantage of this technology compared to alternative designs is not fully realized. In most cases, however, customers may choose CoreGLO panels due to their lower cost and unique design features even if these panels have lower efficacies than the competition.

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[1] The Design Lights Consortium (DLC, www.designlights.org) is an energy efficiency program sponsored by the Northeast Energy Efficiency Partnerships (NEEP) which maintains a Qualified Product List (QPL) of high efficiency products which have met or exceeded pre-defined category requirements.

Furthermore, in some forms of ambient illumination as well as in architectural and decorative/artistic lighting, the efficacy has a secondary consideration compared to the design features. Many state-of-the-art lighting systems in those categories employing solid-state light sources such as LEDs or organic LEDs (OLEDs) have relatively lower efficacies, often in the 40-80 lm/W range. For these applications, CoreGLO is already in a high-performance category in terms of efficacy. In addition, CoreGLO panels readily provide thin and flexible forms traditionally associated only with flexible OLEDs which cost about an order of magnitude more than CoreGLO panels and have efficacies generally below 65 lm/W. Therefore, for applications requiring thin and flexible forms, the value proposition and performance parameters of CoreGLO panels appear to be highly competitive even at the current early stage of development.

Light Output

For linear suspended luminaires, the DLC QPL Technical Requirements V4.4 prescribe minimum light output of 375 lm/ft. This translates to 1500 lm for a 4 ft. product and 3,000 lm for 8ft fixtures. The output of actual commercial suspended lights ranges from about 2,000 lm to 10,000 lm for 4 ft. products and from about 4,000 lm to 20,000 lm for 8 ft. products.

For troffers, which represent another type of linear lights that dominates the commercial buildings market, the minimum DLC requirements are 1,500 lm regardless of the fixture size. However, from a practical standpoint, this minimum may be too low, resulting in a relatively dim appearance of the luminaire and material waste, considering that troffers have relatively large sizes compared to other forms of luminaires. The main bulk of commercial troffers today have light output between 2,000 lm and 5,000 lm for 2′x2′ products and 3,000 lm and 8,000 lm for 2′x4′ products (U.S. DOE, 2018). There are some outliers in this category with lumen packages far exceeding 8,000 lumens. However, that high lumen packages can be perceived as glare, especially when the luminous surface is smaller than the size of the fixture and with the low mounting heights of troffers (typically 8'–12').

The CoreGLO technology provides the opportunity to design lighting luminaires that emit light from the entire area of the luminaire, without producing hot spots. Therefore, CoreGLO panels may allow for packing more lumens per unit area than conventional linear suspended light and troffers having the same size but either smaller light emitting area or non-uniform emission. Additionally, panel configurations that provide both direct and indirect lighting may be allowed for even higher total lumen output, without producing significant glare, since a part of the emission will be directed away from the viewer’s eyes.

In view of the above considerations, the lumen package design constraints for CoreGLO panelsin the linear lighting and troffers category may be broadened compared to those currently accepted in the lighting industry to include the range from about 500 lm/ft^2 to about 3,000 lm/ft^2, which is expected to cover 90 percent or more potential use cases for this technology in general illumination markets. However, it should also be understood that for some types of architectural, decorative and specialty lighting, the lower extremity of the required lumen package may be as low as 100-250 lm/ft^2, especially in cases where the CoreGLO luminaires are used as complementary light sources to other illumination systems.

Color Quality

Most LED-based linear lighting fixtures being sold today have the Color Rendering Index (CRI) in an 80-86 range. A small subset of luminaires (typically in a higher-end category) has CRI values of 90 or greater. The Correlated Color Temperature (CCT) varies from about 2,700 K to about 5,500 K from product to product.

Lucent Optics panels have been previously prototyped with LED packages having CRI of 82 and CCT of 5,000. These color characteristics technically fit into the existing lighting luminaire mix and also meet the typical quality bar of CRI ≥ 80 and CCT ≤ 5,000 (e.g., according to the current DLC requirements). However, further enhancing the color rendering and providing lower-CCT options can further improve the competitiveness and applicability range of CoreGLO panels, especially in high-end luminaire markets. Furthermore, LED-based lighting panels with CRI of 90 or higher, CCT of 4,000 K or less, and 45 lm/W efficacy can be certified to the California Energy Commission as High Efficacy Light Sources[2] for better compliance with Building Energy Efficiency Standards.

In light of the current market trends and regulations, it is believed that further improvements of the technology should consider expanding the selection of CoreGLO panel options to CRI of 90 or greater and CCT of 4,000 or lower, even considering that selecting higher-CRI and lower-CCT LED sources may lead to some drop in efficacy, potentially up to 15-20 percent.

Emission Pattern

In general lighting, the main purpose of a luminaire is typically to provide high enough light output for illuminating a given area while minimizing glare. This is best achieved using wide-area luminaire designs (such as with the form factors similar to 1′x4′, 2′x2′ and 2′x4′troffers) that emit highly diffuse light. The conventional LED lighting presents certain challenges since individual LEDs can be extremely bright, causing glare and discomfort for building occupants if their light emission is not sufficiently diffused. The requirements to hide individual LED sources from the viewer and to distribute light over as wide area of the luminaire as possible impose significant constraints on traditional designs and often require employing sophisticated optics in LED luminaires which leads to overdesign, increasing manufacturing cost of the lighting fixture, and sometimes even considerable loss of energy efficiency.

The principal design of CoreGLO panels inherently hides the LED sources and allows for distributing the emission overt the entire area of the luminaire. However, the surface brightness distribution and angular distribution of the emission from the panel are controlled, in a large part, by the technology employed for extracting light from the light guiding sheet. Considering that the use of relatively thick, high-power optical diffusers may adversely affect the cost, flexibility and optical efficiency of the panel, the design strategies for CoreGLO panels should preferably include using light extraction technologies that produce maximum diffusion without undue reliance on such high-power diffusers. Therefore, designs producing angular emission patterns that closely resemble the emission pattern produced by an ideal diffusely reflecting surface (the so-called Lambertian emission pattern) such that the apparent

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[2] 2016 Building Energy Efficiency Standards, Appendix JA8 – Qualification Requirements for High Efficacy Light Sources.

brightness of the light panel can be about the same regardless of the observer's angle of view, would be particularly useful.

On the other hand, some general lighting applications require other angular distributions, including, for example, “batwing” patterns, which may allow for reducing the light fixture count for a given space. Some applications will also benefit from a more directional output with a reduced side glare, which is generally recommended for spaces having computer screens. Therefore, to cover maximum potential applications, CoreGLO panels should ideally be designed with several options for the angular distribution of the emission to fit specific use cases.

Lifespan, Reliability, and Lumen Maintenance

As with any LED-based lighting system, the CoreGLO panels are expected to decline in lumen output over time due to a gradual reduction in the emission of the LED packages used to generate light in the panel. Therefore, lighting luminaires employing these panels should be designed with the associated light loss factor in mind.

The light loss factor and the useful life of a CoreGLO panel can be conventionally defined based on the L_{70} criteria currently accepted in LED lighting.[3] Today’s white-light LED products are considered to have a good quality if they have a useful life of 30,000 to 50,000 hours or longer. Accordingly, CoreGLO panels should be designed to have a lifespan at least in that range and, even more preferably, in the range from 50,000 to 75,000 hours or longer.

Other lifespan and reliability factors should also be considered. While the use of many LED packages distributed along the edge of the panel can help mitigate the effects of potential catastrophic failures of individual LEDs, electronics and various thermal interfaces used in the CoreGLO panel bey be a source of catastrophic failures on their own. Therefore, to ensure a long-life expectation for the Core-GLO based lighting products, those components should be designed to outlast the LED degradation to the L_{90} level.

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[3] L_{70}: the point in luminaire (or LED) usage time when the luminous flux output has declined to 70% of its original value. Similarly, L_{90} is the usage time point) when the luminous flux output has declined to 90% of its original value.

CHAPTER 4:
LED Module Development

LED Module Design

At the beginning of the project, there were a variety of linear LED modules available on the market. Earlier-generations of the CoreGLO panels were even made using some of those modules. However, it was recognized that additional opportunities existed to minimize the profile of the LED engine and hence further reduce the overall thickness of the panels by developing a new LED module that would be specifically optimized for CoreGLO panels and their thin and flexible forms. The project team also identified fabrication challenges that could be reduced or resolved by selecting particular types of LEDs and more tightly controlling the manufacturing tolerances in the finished LED engines. Therefore, the project team decided to develop a dedicated LED module.

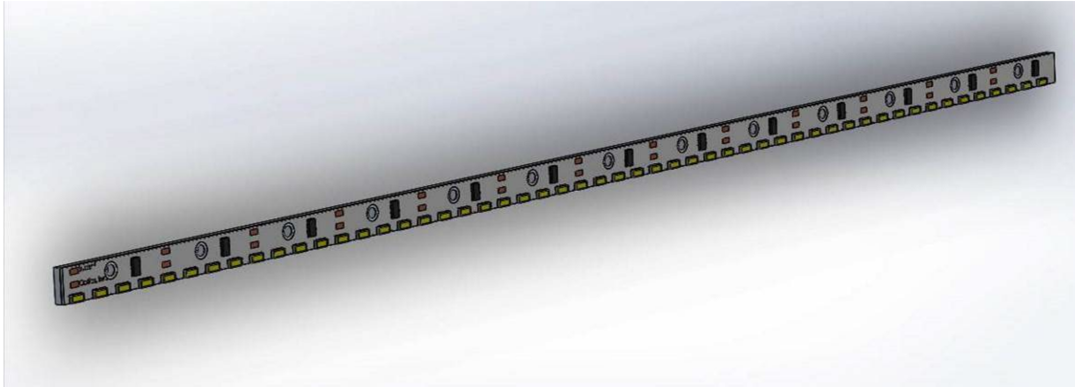
In this development effort, the project team performed component-level analysis and prioritizing the design improvements according to the cost to performance and complexity to performance ratios. The principal structure of the panel was also reworked and a lightweight frameless design with a symmetrical configuration (having two low-profile LED modules at both ends of the panel) was finally adopted.

Rationales for selecting the design with two symmetrically disposed LED engines included facilitating the manufacture of sufficiently large light emitting areas (such as up to 2 feet by 4 feet or larger) and achieving a more efficient heat distribution in the panel (compared to one-sided input). The frameless design was selected for several reasons, including enabling flexible forms and the customization of the panel size and dimensions without changing the panel's principal structure and manufacturing process from one configuration to another.

The project team considered a number of mid-power, high-efficacy LED types that were available in packages having the efficacies in the range from 160 to 188 lm/W at the time, depending on the correlated color temperature/CCT and color rendering parameter/CRI. The priority was given to small form-factor packages to facilitate light coupling, while other considered factors included the LED package cost, availability, performance parameters, and suitability for mass production of the modules.

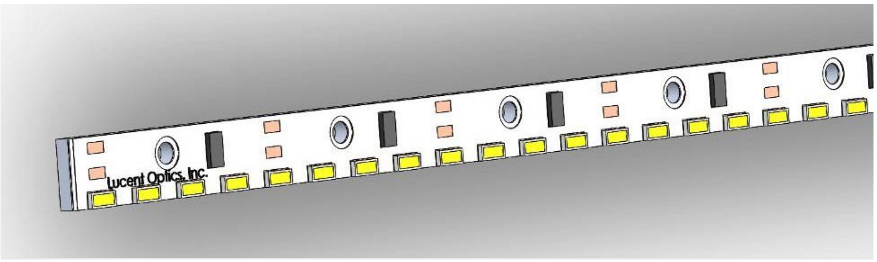
The new LED module was designed as a rigid metal-core LED strip that is 12 inches long and about ¼-inch wide. A solid model of the module is depicted in Figure 4 and its close-up view is shown in Figure 5. The electrical part was designed such that each individual strip could output 1,100-1,500 lumens (depending on the CRI and CCT parameters of LED packages) while consuming slightly less than 9W of power and that multiple strips could be chain-connected to build longer linear LED engines up to 48" in length. The 12-inch standard length was selected primarily out of convenience for making troffer-size lighting fixtures. The target working plug-in efficacy of the module was in the range of 135-150 lumens/Watt, depending on the selection of Color Rendering Index (CRI) and Color Correlated Temperature (CCT) of the LED packages (which are available from the selected vendor at the levels acceptable for commercial linear light fixtures, including 80 and 90 CRI and CCT from 2700 K to 6500K).

Figure 4: Solid Model of the Low-profile LED Module



Source: Lucent Optics, Inc.

Figure 5: Close-up Detail of the Module

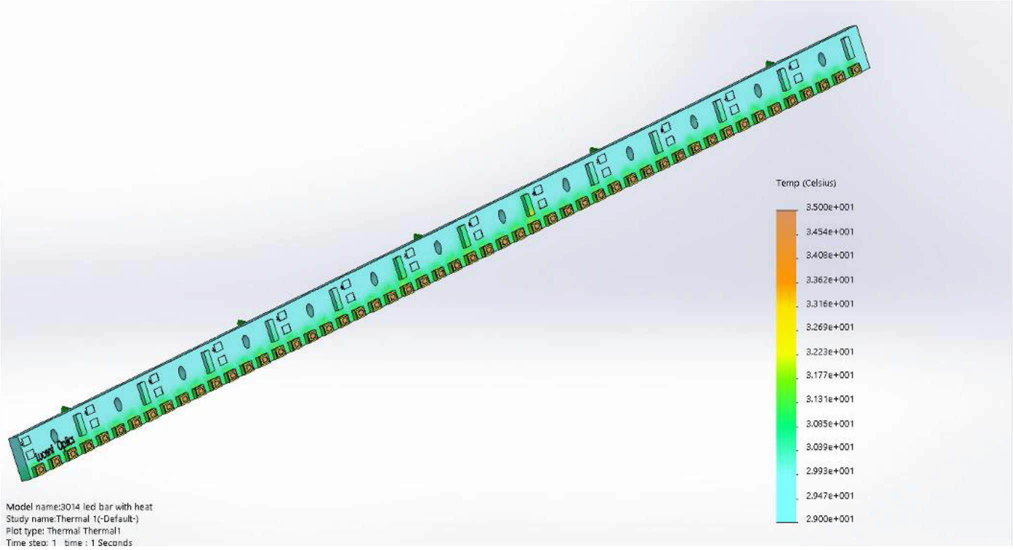


Source: Lucent Optics, Inc.

The thermal analysis of the module under anticipated power loads has shown that the thermal interfaces and overall design of the LED strip were adequate for efficient heat spreading at the target operating parameters. Figure 6 shows the initial modeled temperature distribution for the bare LED strip approximately 10 seconds after switching on, and Figure 7 depicts a steady-state temperature distribution across the module after a prolonged operation time. As it can be seen, the peak temperatures did not exceed 30°C above ambient in the modeled stand-alone operation (without any additional heat sinks or structural components).

Figure 8 shows the modeled temperature distribution for the same module mounted to a heat-dissipating housing of the LED engine which provides additional surface area and aids in passive heat sinking/dissipation. The results indicate that the temperature differential with the ambient can be reduced by at least an additional 5-10°C when the LED strip is assembled within the LED engine of a CoreGLO panel and fall within an acceptable range. Accordingly, the thermal characteristics of the designed LED strip and module were deemed to be adequate for most CoreGLO implementations.

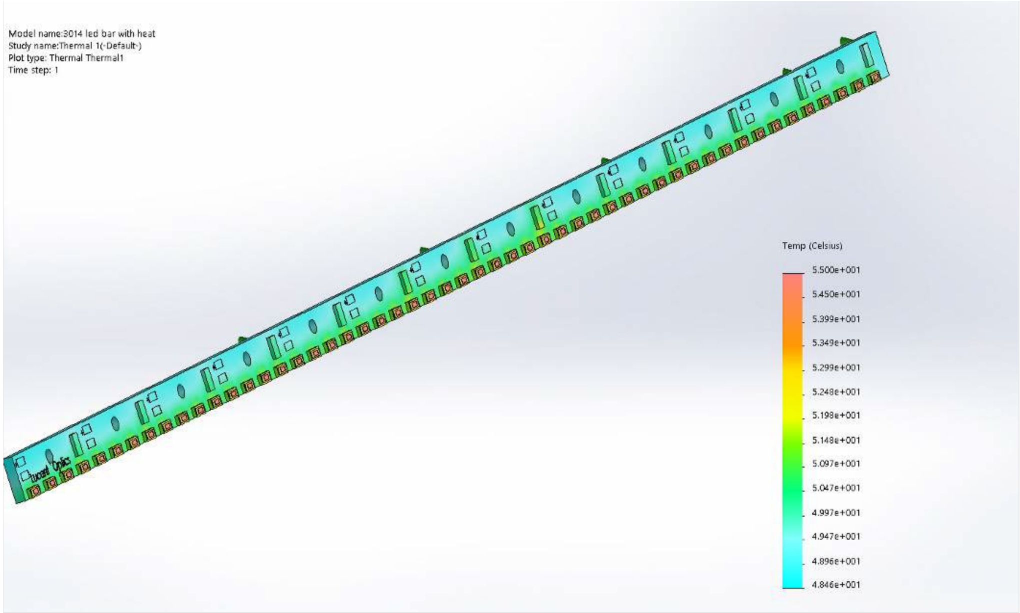
Figure 6: Initial Temperature Distribution for the Bare LED Strip



About 10s after switching on.

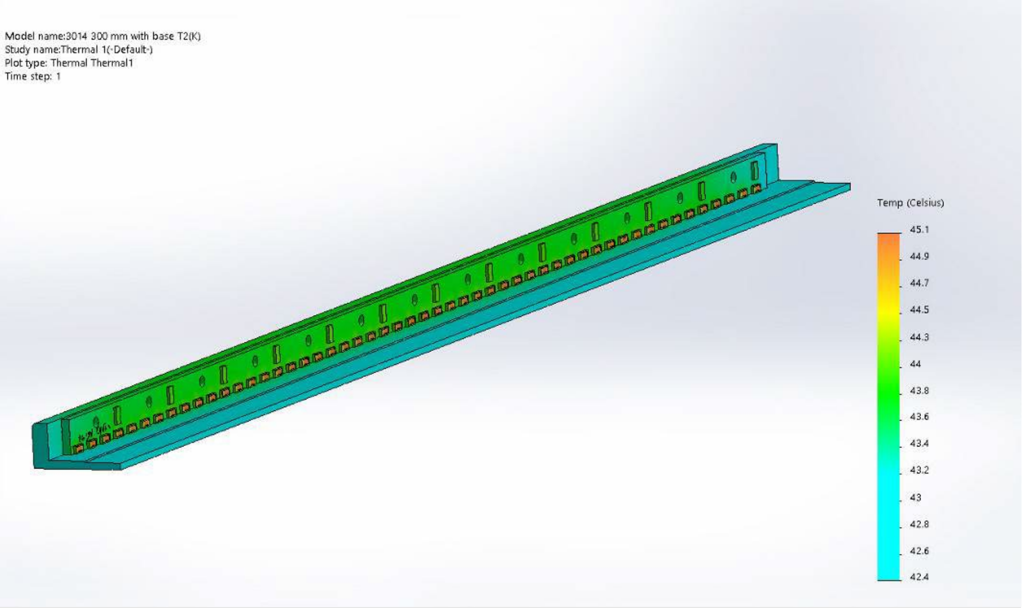
Source: Lucent Optics, Inc.

Figure 7: Steady-state Temperature Distribution



Source: Lucent Optics, Inc.

Figure 8: Temperature Distribution for the LED Strip Mounted to a Heat-dissipating Housing Channel



Source: Lucent Optics, Inc.

LED Module Prototyping

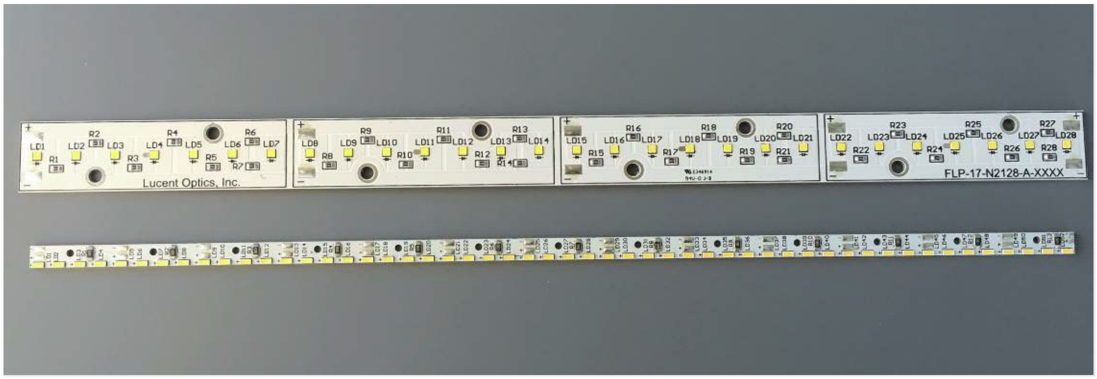
Prototyping of the developed 12-inch linear LED modules was performed at an ISO 9001 certified industrial facility. Each LED strip in the modules was made cuttable in series of 4 LEDs to enable making panels that are smaller than 12 inches and "non-standard" size panels. Figure 9 shows a photograph of the LED packages used for making the new LED modules.

Figure 9: Mid-power LED Packages Used for Making New Linear LED Modules

Source: Lucent Optics, Inc.

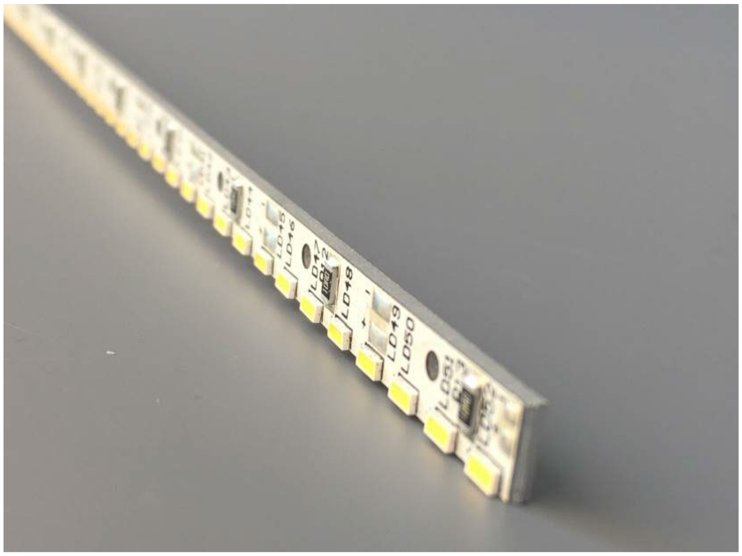
As discussed, the ¼-inch width of the new module was roughly a third of the width of the earlier designs (Figure 10). It also featured an asymmetric placement of the LED packages on a metal-core PCB, near an edge of the strip (compared to the previous central placement of the LEDs on the underlying PCB strip). All this allowed for significantly reducing the profile and weight of the LED module by redesigning the housing to conform to the smaller form factor of the LED strip. A close-up view of the new LED module is shown in Figure 11.

Figure 10: Comparison of the Newly Developed *Low-profile* LED Module (bottom) and the Earlier LED Strip Design (top)



Source: Lucent Optics, Inc.

Figure 11: Low-profile LED Module



Modules has improved compatibility with thin and flexible (CoreGLO) lighting panels.

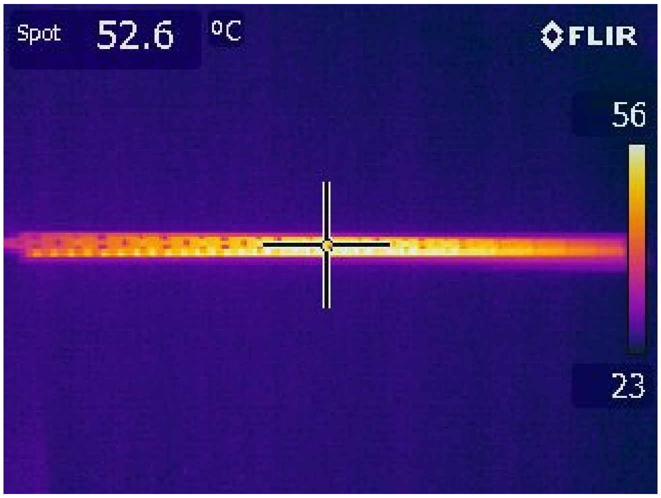
Source: Lucent Optics, Inc.

One of the trade-offs of the new LED module design was the requirement of higher manufacturing tolerances and strengthening the core of the housing compared to the previous design. This requirement was deemed necessary to provide a sufficient structural rigidity and consistent coupling of the LEDs to the light guide along the entire length of the module to minimize the light spillage in the CoreGLO panel.

LED Module Testing

Basic tests of the operating regimes of the LED modules were performed in-house, which included power consumption measurements and thermal performance tests. A thermal image of a stand-alone LED module in an illuminated state is shown in Figure 12. The measured heat distribution generally agreed with the thermal model, showing a maximum temperature of the LED strip within 10 percent of the modeled one for the same electrical power input.

Figure 12: Thermal Image of Individual LED Strip in Illuminated State



Source: Lucent Optics, Inc.

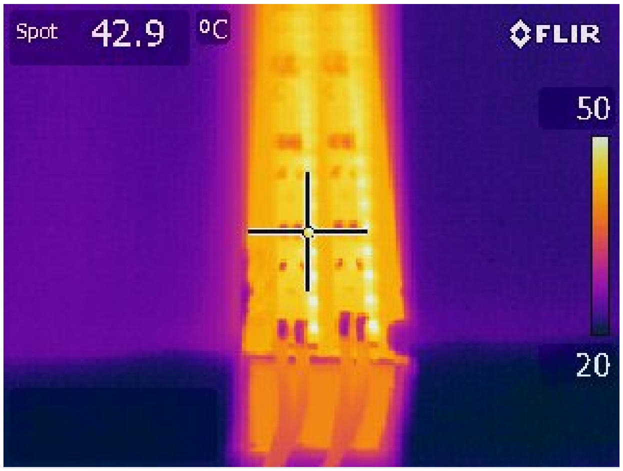
For evaluating the light output, power consumption and luminaire-level efficiency of the LED modules, four individual LED strips were assembled on a heat-spreading base and powered by a commercially available 12V power supply/LED driver. The experimental LED module assembly used for measuring module performance is shown in Figure 13. The sizing of the test module assembly and the number of LED strips were selected to approximately match a 2ft x 2ft, 35-Watt CoreGLO panel which could be fit into a standard-size opening in commercial suspended ceilings, similarly to the conventional 2’x2’ lighting troffers.

Figure 13: Test LED Module Assembly

Source: Lucent Optics, Inc.

A thermal image of the experimental LED module assembly being in an illuminated state is shown in Figure 14. The peak temperatures on the surface of the LED modules were about 30°C above ambient in a steady state, which was in agreement with the expectations based on earlier thermal modeling. The use of a heat spreading substrate allowed for reducing the temperature variations along the LED modules compared to a stand-alone module, ensuring similar operating conditions for the LED packages during the electrical and optical tests.

Figure 14: Thermal Image of the Test LED Module Assembly in Illuminated State



Source: Lucent Optics, Inc.

Detailed electrical and optical tests were further performed by Light Laboratory[4], an NVLAP[5] accredited, CEC-approved lighting test lab. The tests included measurements of the total luminous output from the LED module as well as its efficacy and angular distribution of the emission using a type-C Goniophotometer in accordance with IES LM-79-08 protocol. The measured luminance data of the LED module are listed in Table 1 and the angular candela distribution is shown in Figure 15.

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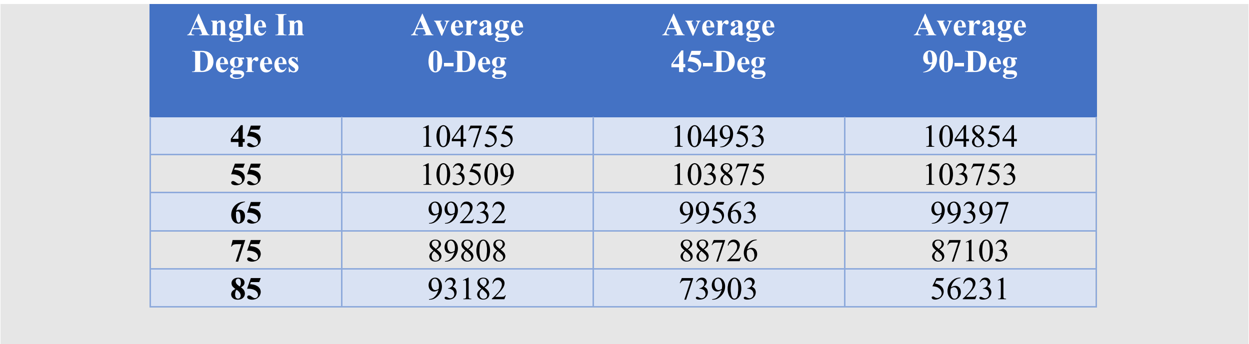
[4] Light Laboratory Inc. is a CEC Title 24 Approved Test Lab which provides Test Reports in accordance with IESNA LM-79-08 and CEC-400, APPLIANCE EFFICIENCY REGULATIONS, (Sections 1603 & 1604(n) and Tables K-1 through K11, N1 through N3).

[5] National Voluntary Laboratory Accreditation Program (NVLAP).

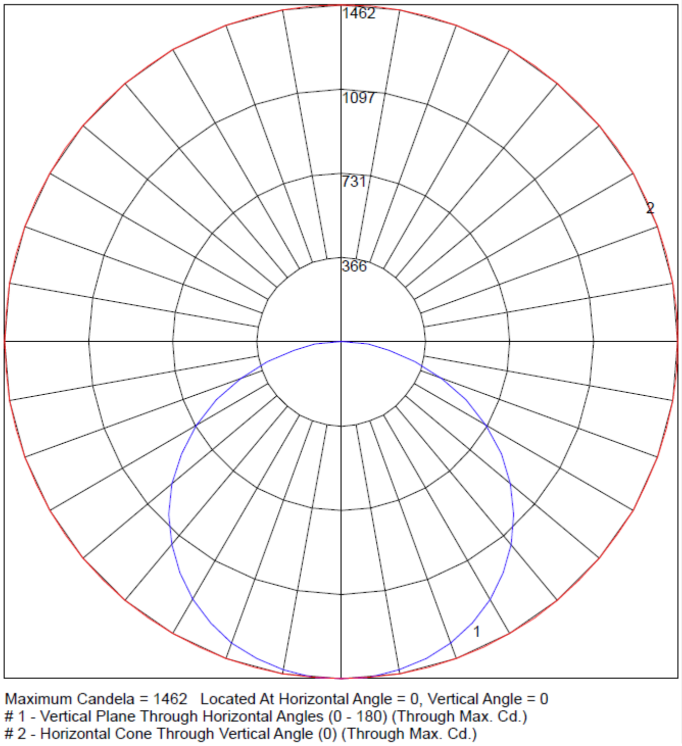
Table 2: Luminance Data (cd/sq.m)



Angle In Degrees	Average 0-Deg	Average 45-Deg	Average 90-Deg
45	104755	104953	104854
55	103509	103875	103753
65	99232	99563	99397
75	89808	88726	87103
85	93182	73903	56231

Source: Lucent Optics, Inc.

Figure 15: Candela Distribution of the Experimental LED Module Assembly

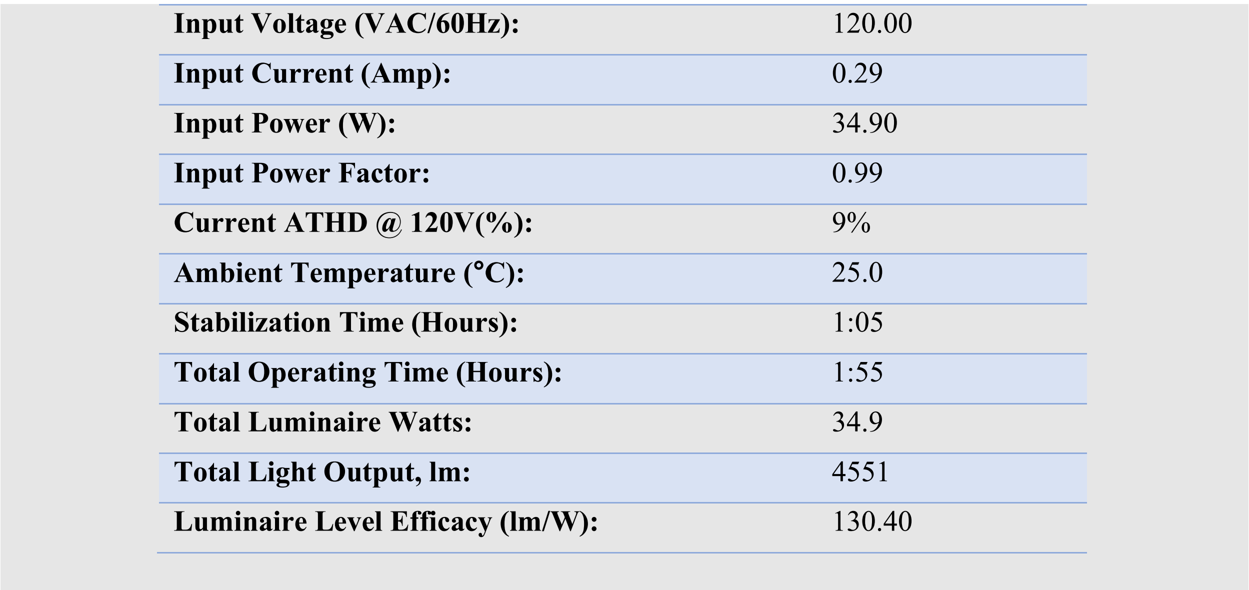


Maximum Candela = 1462 Located At Horizontal Angle = 0, Vertical Angle = 0
1 - Vertical Plane Through Horizontal Angles (0 - 180) (Through Max. Cd.)
2 - Horizontal Cone Through Vertical Angle (0) (Through Max. Cd.)

Source: Lucent Optics, Inc.

The total light output of the module was measured at 4,551 lumens at a 34.9 W electric power input. This corresponds to a 130.4 lm/W efficacy and includes the losses in the LED driver (see Table 2).

Table 3: LED Module Test Summary



Input Voltage (VAC/60Hz):	120.00
Input Current (Amp):	0.29
Input Power (W):	34.90
Input Power Factor:	0.99
Current ATHD @ 120V(%):	9%
Ambient Temperature (°C):	25.0
Stabilization Time (Hours):	1:05
Total Operating Time (Hours):	1:55
Total Luminaire Watts:	34.9
Total Light Output, lm:	4551
Luminaire Level Efficacy (lm/W):	130.40

Source: Lucent Optics, Inc.

In comparison, T8 and T12 fluorescent tubes have efficacies in the range of 80-96 lm/W. Therefore, the performance of the developed LED module was deemed sufficient for making high-efficiency CoreGLO panels that could replace the traditional fluorescent lighting fixtures. It should also be noted that the efficacy of the module can be further increased by using higher-efficacy LED packages. As the LED technology keeps evolving and new high-performance LEDs become available, the performance of CoreGLO LED module of the developed design could be further improved in the future as part of the overall CoreGLO technology development.

The project team further evaluated the measured performance data for the new LED module, identified strategies for further improvements and refined design parameters to optimize the module for maximum efficacy and heat dissipation. Further optimizing the electrical circuits and thermal design were among such strategies and design improvements. For example, it was determined that some of the electronic components utilized in the module could be eliminated to further increase the overall efficacy. It was also decided to increase the operating voltage from 12 VDC to 24-36 VDC to reduce the resistive losses within the module circuitry, which should further improve the light output and efficacy, as well as reduce thermal buildup. Additional improvements in the metal-core PCB structure of the module to enhance heat spreading and dissipation have also been considered.

CHAPTER 5:
Light Guiding Substrate Development

Design Considerations for Light Guiding Substrates

The project team has identified several critical requirements for the light guiding substrates in the context of making thin and flexible waveguides for CoreGLO lighting panels. Their requirements are briefly discussed below.

Optical Transparency

The material of the substrate should have an exceptional bulk optical transmittance and low haze since it should be able to guide light from one edge to another without appreciable absorption or scattering. The criticality of this requirement further increases with the increase of the size of CoreGLO panel. In addition, the material should exhibit no yellowing after prolonged exposures to high fluencies of LED light and no color filtering in the visible range (such that there is no appreciable color shift along light propagation path from one edge to another).

Surface smoothness

Any surface irregularities can negatively impact the light guiding ability of the substrate, causing premature light extraction and making it difficult to achieve high uniformity and desired angular distribution of the emission. Therefore, the surfaces of the processed sheets must be very smooth, with highly polished finish. It was determined that the root-mean-square (RMS) surface roughness parameter characterizing the surfaces should preferably be below 10 nanometers (nm).

Flexibility

The bendability of the plastic substrate with relative ease and without breaking is of a great importance for making curved and flexible CoreGLO panels. While curved shapes can be obtained for most thermoplastics using thermoforming, this is not always practical from the luminaire design and manufacturing perspective. For example, adding thermoforming increases the cost and energy consumption into the fabrication process, complicates product storage and shipping, and may also produce unwanted residual stresses in the material. Furthermore, when repeated waveguide bending is required during luminaire handling, storage or operation, using inflexible substrates is basically precluded.

Weatherability, heat-, UV-, and impact resistance

Depending on the design of CoreGLO-based luminaire, the light-distributing waveguide may be either entirely encased within the luminaire or have one or more its surfaces exposed to the environment. Accordingly, weatherability and resistance of the light guiding substrate to abrasion, UV, moisture, chemicals, etc., should also be factored into the material selection. The useful lifespan of the material should at least match or exceed the lifespan of LED packages used in the CoreGLO panels (e.g., 50,000 – 100,000 hours). Even when the light guide is not exposed, good UV resistance may still be required when LEDs' emission includes wavelengths in the UV spectrum. Scratch and impact resistance can also be important for luminaire designs with light guides which are intended to be used in harsh environment or made for repeated flexing.

Heat deflection/resistance

In CoreGLO luminaires, one or more edges of the light guide is typically located within the housing of an LED engine and can be disposed in contact with the walls of the housing. While the housing is typically designed to efficiently dissipate the heat generated by the LEDs, its temperature can be often 20°C or more above the ambient. Accordingly, light guiding substrate material should be able to withstand temperatures well in excess of 60°C (and preferably above 80°C), including repeated thermocycling, without performance degradation or loss of integrity. For example, some common polymeric materials such as polyolefins can warp and distort at elevated temperatures, which could negatively impact the performance of the luminaire and thus should be avoided for using in waveguides that are to be used in a close proximity of LEDs.

Surface wettability

In order to make a CoreGLO panels, the plastic sheet intended for distributing and emitting light must be converted into an optical waveguide by patterning its surface for light extraction. In the context of CoreGLO technology, a preferred patterning technique involves UV printing of small light extraction features on the surface of the sheet. Accordingly, the substrate material should be compatible with such patterning and should have a good surface wettability and excellent receptivity/adhesion of UV ink.

Dimensional stability

Although CoreGLO luminaires are primarily intended to be used in an indoor environment, interior temperatures may still vary in a broad range. Furthermore, parts of the light guiding substrate located within the heat-dissipating housing will also be repeatedly exposed to elevated temperatures, following the "on" / "off" cycles of the fixture's operation. The dimensional stability of the material is also particularly important for maintain good optical coupling between the LEDs and the light guide and for achieving maximum luminous efficacy of the lighting fixture.

Cost

Even though the thickness of the waveguide in CoreGLO panels is reduced by 3 to 10 times compared to traditional edge-lit panels, the bulk cost of the substrate material remains of a critical importance since it is still a factor determining the manufacturing cost of the luminaire. On the other hand, at ultra-low thicknesses of the waveguide, somewhat higher costs of the substrate material could be tolerated if that material provides clear advantages in other categories.

Commercial availability

Finally, the broad availability of the substrates from multiple vendors is important from the technology scale-up point of view. Commoditized materials can be even more preferred to provide the ability to satisfy the potential future demands for thin/flexible LED lighting panels.

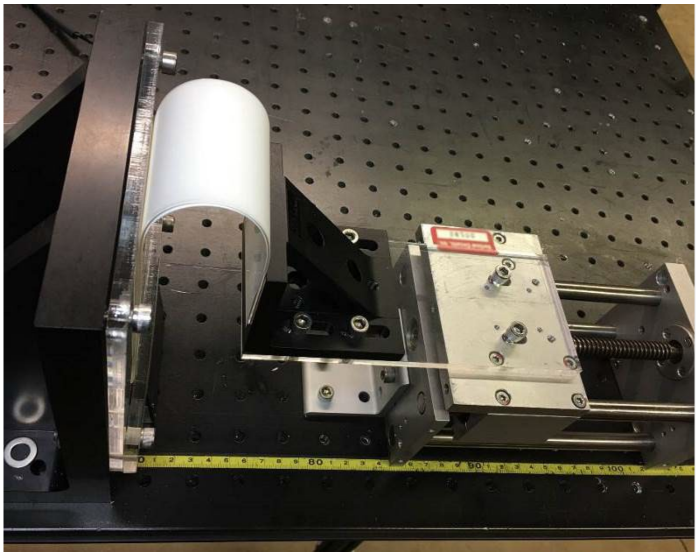
Material Selection

Several candidate materials have been investigated and some were further tested for the use in optical waveguides of the CoreGLO panels. Exemplary common materials considered in this study included optical-grade Polymethyl methacrylate (PMMA), methacrylate styrene copolymer (MS), Polycarbonate (PC), Polystyrene (PS), Styrene methyl methacrylate (SMMA), and Polyethylene Terephthalate Glycol (PETG).

Optical tests used for the final down selection of the materials included measuring the transmittance and haze of candidate plastic sheets at various thicknesses. The transmittance was also measured in a waveguide mode, in which light was propagated along the length dimension of plastic sheet substrates. The waveguide-mode transmittance is particularly important for CoreGLO where light is guided relative long distances (up to the length and width of the lighting panel) through the material and where even a relatively small rate of absorption or haze may cause a significant reduction in optical efficiency.

Mechanical tests of the candidate plastic substrate materials particularly included flexibility tests. This type of characterization is not typically provided by plastic sheet manufacturers, but the ability of the substrate to flex to relatively tight radii of curvature without breaking can be important for CoreGLO products that require curved shapes. Figure 16 shows one of the flexibility tests for a candidate waveguiding substrate material.

Figure 16: Flexibility Test of Light Guiding Plastic Substrate



Source: Lucent Optics, Inc.

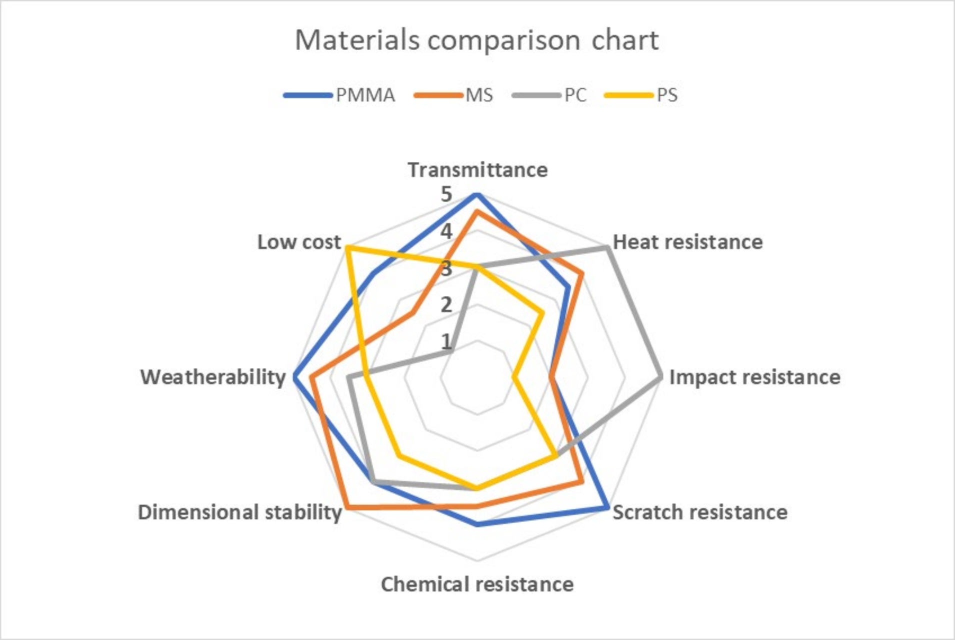
PMMA, which has proven to work sufficiently well in earlier prototypes of CoreGLO panels, was found to have the best bulk optical transmittance (in the visible spectrum including the emission of LED sources), weatherability, scratch resistance and broad commercial availability. It was also confirmed to be one of the best materials suitable for cutting using a CO_2 laser. The CO_2 laser cuttability was found to provide certain benefits in automating the fabrication process and meeting higher tolerance requirements.

SMMA has shown optical properties similar to PMMS acrylic and also demonstrated a superior workability, chemical and moisture resistance, albeit as a cost premium. MS was found to possess certain advantages in mechanical stability since it has 40 percent lower coefficient of thermal expansion (CTE) and 2.5x lower humidity swell than PMMA, which is important for maintaining the reliable light coupling between LEDs and the light guiding substrate in CoreGlo panels.

As it was expected, PC has shown a much superior impact resistance and heat deflection. However, it lagged significantly behind other selected optical plastics in optical transmittance and affordability. PS featured the lowest cost per volume and unit area but generally lacks the performance of other candidate materials.

And, finally, PETG, which is an amorphous glycol-modified variation of PET, has shown has excellent processability and good receptivity of UV ink. While its clarity and chemical resistance were deemed good when compared to other modifications of PET and many other plastics, its bulk optical transmittance was found to be considerably lower than that of PMMA in all formulations tried. A comparison matrix of several candidate optical materials is shown in Figure 17 and their most relevant propertied are summarized in Table 3.

Figure 17: Comparison Matrix for Candidate Optical Materials



Optical materials suitable for making the light guiding substrate of CoreGLO™ panels.

Source: Lucent Optics, Inc.

Optical grade acrylic (PMMA) in three different formulations available from various manufacturers was finally selected for the subsequent development and prototyping of CoreGLO panels. The selection was made based on a combination of factors, including optical performance, mechanical stability, eco friendliness, ease of working with, weatherability, as well as cost and availability. The down-selected materials were procured and tested for the compatibility with different light extraction patterning processes including cutting/patterning using laser ablation and UV printing/patterning. All of the materials were found compatible with both patterning processes. Some differences in the material and surface properties (such as surface energy/wettability) between the materials were noted and accounted for in the subsequent tasks directed to finalizing and further developing the light extraction patterning technique.

Table 4: Typical Properties of Several Tested Substrate Materials

Material/property	Acrylic (PMMA)	Polycarbonate (PC)	SMMA	PETG	Polystyrene (PS)
Light transmittance, %	92-93	86-88	91	89	87-90
Refractive index	1.49	1.585	1.53-1.55	1.57	1.59
Heat deflection Temperature, °C	90-100	140-145	90-100	70	80-100
Thermal expansion, 1/°C	7×10^{-5}	7×10^{-5}	$6X10^{-5}$	$4X10^{-5}$	7×10^{-5}
Water absorption, %	0.3	0.15	0.12-0.18	0.2	0.2
Hardness	76-80	70-80	75-90	115	80

Source: Lucent Optics, Inc.

CHAPTER 6: Development of Advanced Light Guiding Substrate Patterning Technique

Selection of Substrate Patterning Technique

In this task, the project team evaluated several different techniques for patterning PMMA substrates and converting them into high-performance optical waveguides for large-area CoreGLO panels. The techniques considered for this study included laser ablation, UV replication, hot embossing, screen printing, and UV microprinting.

The UV microprinting process was finally selected for further prototyping and CoreGLO technology development. UV microprinting is a proprietary additive manufacturing process which involves depositing microscopic drops a nanoparticle-loaded light scattering material to the surface of the substrate and curing that material using UV light. Some of the key characteristics and advantages of the UV microprinting which were considered decisive in making the final selection included:

- Inherently high degree of customizability (e.g., size/dimensions, aspect ratio, material thickness, substrate type, and visual appearance of the finished product) due to its additive manufacturing nature.
- Scalability for patterning large-are substrates incrementally expanding the production volumes.
- Low cost, especially in small production volumes. No special requirements for production facilities (although clean-room settings might be beneficial, especially for making high-end, high-visibility products).
- Relatively high repeatability via a fully automated, computer-controlled material deposition process
- Environmental friendliness: no water usage or release of harmful fumes; minimum waste and low electricity demand.
- Compatibility with a wide range of materials (acrylic, glass, polycarbonate, PET, specialty optical plastics).
- Previous experience of the project team with this technique, the availability of existing equipment, software, and established Lucent Optics’ IP positions of in relevant areas.

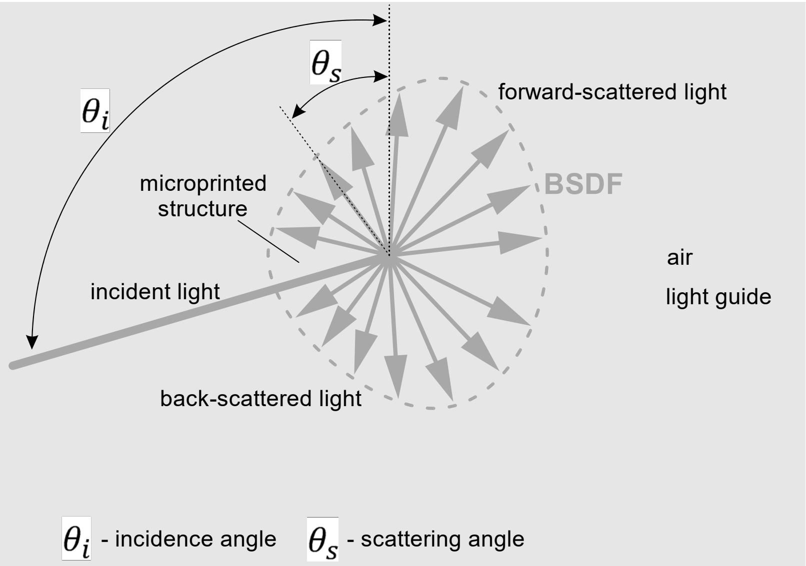
Pattern Generation

The light extraction pattern formed in the surface of the plastic substrate controls the rate of light extraction from the waveguide of the respective CoreGLO panel and essentially defines the panel brightness, its overall light output, optical efficiency, and the intensity profile of the emission across the panel surface. One of the challenges faced by the project team was the necessity to obtain a relatively high level of emission uniformity for each CoreGLO panel while also optimizing the panel for a maximum light output. Building the ability to produce a uniform emission with a given accuracy (such as within 10-20 percent from the average) and, at the same time, producing maximum possible light output can be important for a successful commercialization of this technology in general lighting applications. A further challenge was building the ability to accurately predict the emission distribution from the waveguide and customize CoreGLO panels for various requirements of the end-products, such as providing a custom light output profile across the panel surface. For example, while one product may require a uniform intensity profile, other products may require emitting light in various geometric or decorative patterns. In addition, producing custom geometrical pattern of the emission while maintaining relatively uniform light output from each area of the panel was deemed important for making architectural and decorative lighting fixtures and for differentiating next-generation wide-area LED lighting panels from the incumbent fluorescent technology.

To fully address these challenges in generating the light extraction patterns, it was necessary to perform high-fidelity optical modeling taking into account various parameters of the light guiding substrate and the microprinted surface structures (microstructures). This, in turn, required creating and using a relatively realistic representation of the individual microprinted light extraction features (microstructures). For this purpose, the project team performed actual 3D measurements of the microstructures formed in different printing and UV curing regimes. These measurements were used to define geometrical parameters of the microstructures in the optical model.

Another important step in the modeling was defining the bi-directional scattering distribution function (BSDF) of the microstructures (Figure 18). The microstructure-level BSDF not only determines the angular distribution of the emission, but also directly impacts the rate of light extraction and hence the spatial distribution of the light output from the entire panel. Since measuring BSDF directly on the level of an individual microstructure (which has a size of the order of 0.1 mm and a thickness of only a few microns) is difficult, the project team had to infer or iteratively reconstruct this function based on an iterative process including measurements and empirically determining BSDF parameters that most closely approximate the measured data. An advantage of using this approach was that, once the parameters of pattern generation algorithms are adjusted and validated for a specific material, finished light guides with the prescribed spatial distribution of light emission could be produced on demand and without extensive experimentation. The measurements that were performed for this purpose included capturing light output parameters of the entire microprinted light guide/panel and taking individual spot measurements of luminance at different locations of the light guide. The collected data were then analyzed and used to modify the BSDF parameters in the modeling software which was used to generate new light extraction patterns. The process was iteratively repeated until the measured spatial distribution of the emission from the light guide agreed with the measurements.

Figure 18: Microstructure-level Bi-directional Scattering Distribution Function used in the Optical Models



Source: Lucent Optics, Inc.

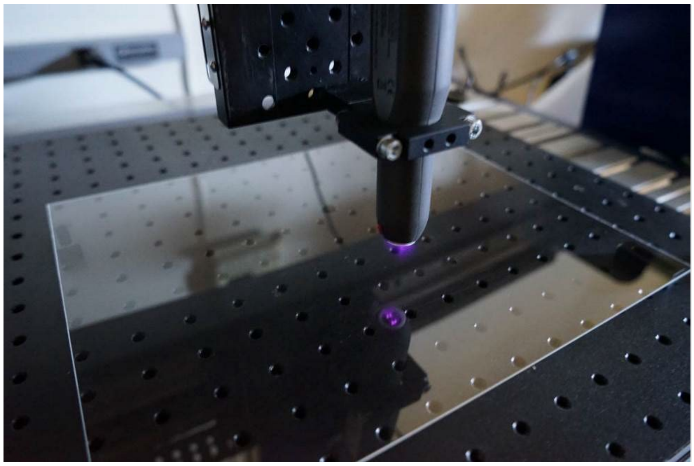
Substrate Preparation for Patterning

Define the manufacturing steps necessary for preparing the substrates for light extraction patterning, various pre- and post-processing processes for substrate preparation have been evaluated. Candidate pre-processing processes particularly include pre-washing the substrate in de-ionized water with and without adding surfactants, ultrasonic-assisted cleaning, using area masks, as well as surface treatment using corona discharge and atmospheric plasma treatment. Post-processing manufacturing steps considered in this evaluation included UV curing and various topcoats for the light extraction pattern.

These processes were found to have a varied degree of impact on the parameters of light extraction features produced by UV printing, mainly due to their impact on the wettability of the surface of the substrate. For example, pre-treating the substrate surface using atmospheric plasma (Figure 19) has resulted in a notable increase in the surface wettability. This, in turn, dramatically improved the quality and repeatability of forming the light extraction features on some grades of PMMA. The improvement is illustrated in Figure 20.

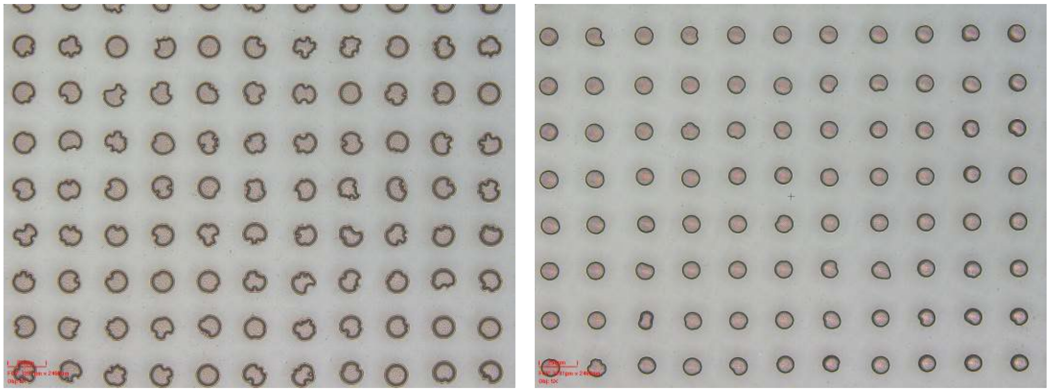
In view of these results, optimizing pre-processing regimes was deemed to be an important part of the CoreGLO technology platform which needed to be further considered in light extraction modeling and waveguide manufacturing process development.

Figure 19: Testing of Substrate Surface Pre-treatment Using Atmospheric Plasma



Source: Lucent Optics, Inc.

Figure 20: Impact of Surface Pre-treatment on the Formation of Light Extraction Features



Left: untreated substrate. Right: untreated substrate.

Source: Lucent Optics, Inc.

Patterning Process

In the UV microprinting process utilized for patterning the plastic substrates, a light-scattering material (UV ink) was fed in a liquid form into an ink-jetting head (Figure 21) and dispersed over the substrate surface according to the previously generated two-dimensional pattern.

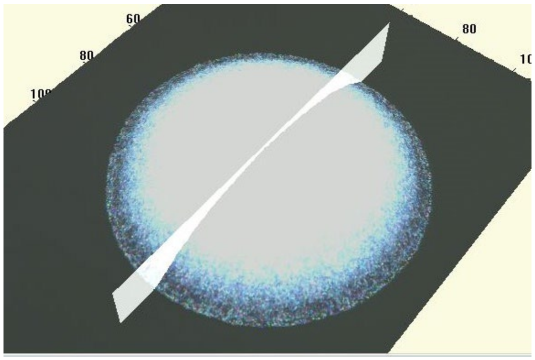
In the current implementation of microprinting, the surface of the plastic substrate designated for extracting light receives from tens of thousands to several million micro-drops of the UV ink in this process, depending on the size of the substrate. Despite the so large number of individual micro-drops, the process is fully automated and takes only a few minutes per panel. The ink contains forward-scattering nanoparticles mixed into an optically clear UV cure resin to maximize light extraction and scattering without absorbing the light energy.

Figure 21: Substrate Patterning Using UV Microprinting Process

Source: Lucent Optics, Inc.

The amount of light scattering material dispensed at each location of the substrate was controlled using the piezoelectric drop-on-demand technology. Using this technology has allowed for controlling the volume of individual micro-drops on a pico-liter level. This level of precision was found important for obtaining the sufficiently high repeatability of the microstructure formation and for ensuring that the right amount of light is extracted at each location of the waveguide. This has also allowed for producing microprinted light extraction microstructures with an extremely small size (around 0.1mm in diameter and only 3-4μm in height), shown in Figure 22. An additional benefit of the so small size and volume of the individual micro-drops was making them virtually invisible to the naked eye and preserving much of the original transparency of the substrate.

Figure 22: 3D Image of Individual Light Extraction Feature



Source: Lucent Optics, Inc.

The density gradient of the microprinted pattern was controlled using software in accordance with the computer-generated pattern obtained using optical modeling and optimization, forming a variable ink density along the surface of the substrate. Replicating the designed density gradient is important for both maximizing the optical efficiency of the lighting panels and achieving a unform surfaces emission by varying the light extraction rate across the panel surface.

The micro-drops were instantly cured to a solid form using a UV lamp and made the resulting light extractions microstructures an integral part of the substrate, effectively creating a two-dimensional pattern of light extraction microstructures and completing the waveguide fabrication process. Figure 23 compares an exemplary design pattern (computer-generated) and its replication on a plastic substrate using the UV microprinting process. The comparison shows a good match between the actual and designated positions of the microprinted light extraction structures, confirming that the microprinting process accurately replicates the intended patterns and density gradients.

Figure 23: Comparison of Computer-generated Pattern (left) and Photo of actually Micro-printed Pattern (right)

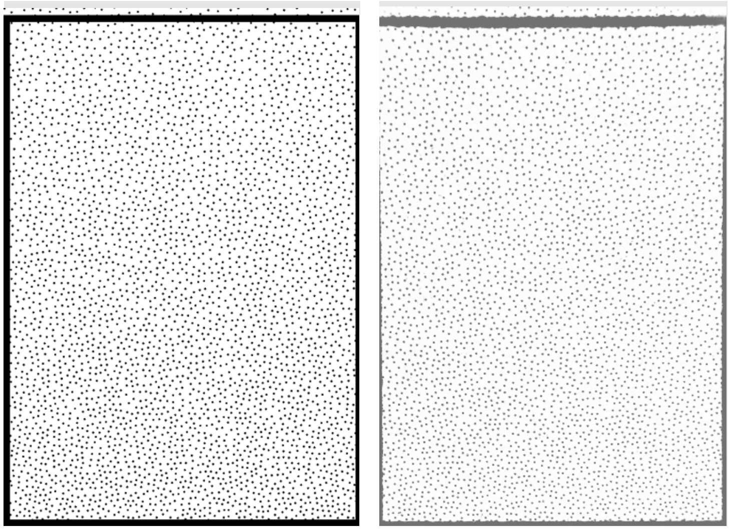


Photo taken using a microscope.

Source: Lucent Optics, Inc.

The UV ink was almost instantly cured using an in-line ultraviolet LED lamp, producing a finished thin and flexible waveguide which could be readily incorporated into a lighting panel without any need for further processing. Since the microprinting process does not involve any mechanical or chemical processing of the plastic substrate the microprinted waveguide retains the mechanical properties and flexibility of the original substrate.

In summary, the microprinting technique used and further developed in this project represents a convenient and relatively inexpensive additive manufacturing process which can be realized at conventional light-manufacturing facilities both in low volumes and on a medium commercial production scale. Depending on the design of the target lighting luminaire using the CoreGLO technology, a microprinted waveguide can be the only optical element needed to complete the luminaire. However, CoreGLO panels may also contain other layers, such as lighting diffusers or protective sheets, depending on the end-product design.

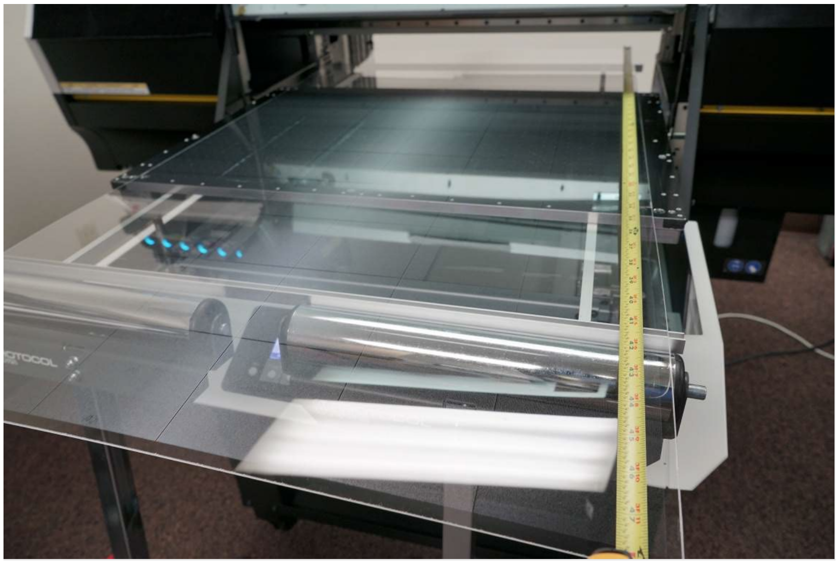
Notably, the light extraction pattern can be quickly reconfigured without any need for retooling or any change in the manufacturing process, thus providing enhanced customization capabilities for the targeted lighting products. Microprinting was also found to be extremely material efficient, requiring only a fraction of a milliliter of the liquid UV-curable material to pattern the waveguide for a troffer-size CoreGLO panel. This means that thousands of waveguides can be patterned using just about 1 liter of consumables. Unlike other methods of making luminaire parts, this additive manufacturing process may be regarded as highly sustainable since it uses very small amounts of energy (<0.025 kWh per square meter of waveguide), does not involve any melting or chemical processing of the substrate, and does not generally require the use of water or harsh chemicals, such as solvents.

Scaling Up the Patterning Process to Large-area Substrates and Prototyping of Custom-Size Waveguides

One attractive market for the CoreGLO panels is retrofitting or replacing fluorescent troffers in commercial buildings where the majority of the fixtures have a 2ft by 4ft form factor. Therefore, it was important to have the CoreGLO technology scaled to those sizes of the patterned waveguiding substrate whole maintaining the thin and flexible forms.

The pattern generation algorithms and the microprinting process have been adapted to create a capability to produce high-performance waveguides from 2ft x2ft (about 60cm x 60cm) to 2ft x 4ft (60cm x 120cm) in size and about 1 mm in thickness for flexibility. Figure 24 shows an exemplary microprinted waveguide manufactured at this maximum size. This represented a significant advancement in Lucent Optics' internal capability of light guide manufacturing, which was previously limited to about 2ft x 1.5ft (60cm x 45cm).

Figure 24: Large-format Patterned Light Guiding Substrate on Completion of the Patterning Process

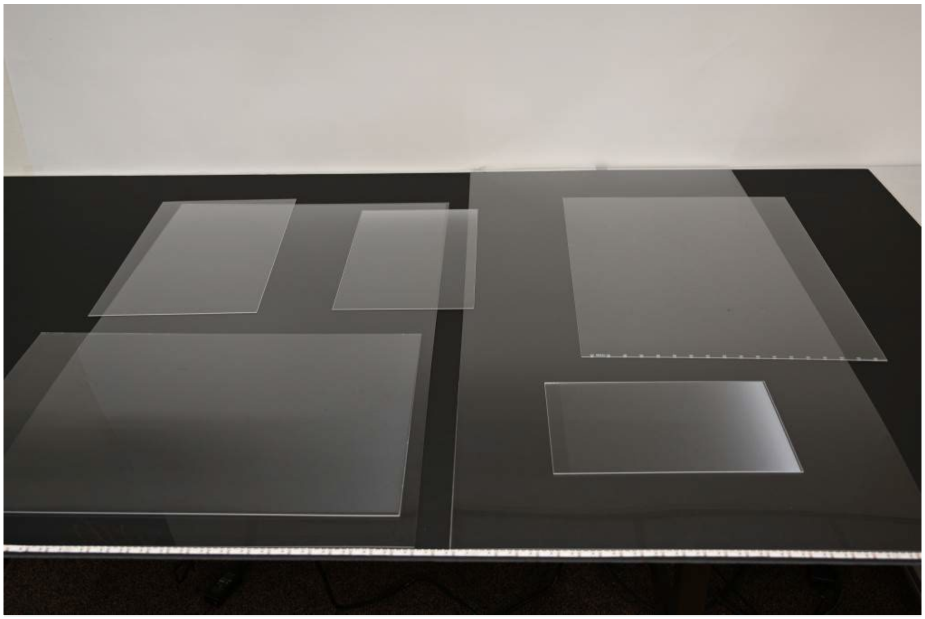


Source: Lucent Optics, Inc.

The project team has further produced a representative experimental set of full-size functional flexible light guides to test the process of patterning flexible substrates with different custom dimensions up to the maximum size. This also helped verify the waveguide manufacturability for various application scenarios involving different formats of the lighting panels. Figure 25 shows several fabricated waveguides with the sizes including 48"x24", 39"x24", 25"x18", 19.5"x11.5", 17"x9.5", and 12.5"x8". The microprinted pattern of each form factor of the finished waveguide substrate had a unique density gradient of the light extraction features. This gradient was designed to produce a relative uniform emission when the light guide is illuminated from either one edge or two opposite edges using the LED linear engines developed earlier.

Measuring the light output characteristics of the light guides with low-profile LED engines indicated that the parameters were well within the designed ranges, also confirming a sufficiently high repeatability of the manufacturing process. It can, thus, be concluded that the enhanced substrate patterning process is suitable for pilot manufacturing and on-demand making of custom-size waveguiding substrates up to the targeted full-size of 24”x48” (the most common size of standard commercial troffers).

Figure 25: Sample Selection of the Patterned Light Guide Substrates



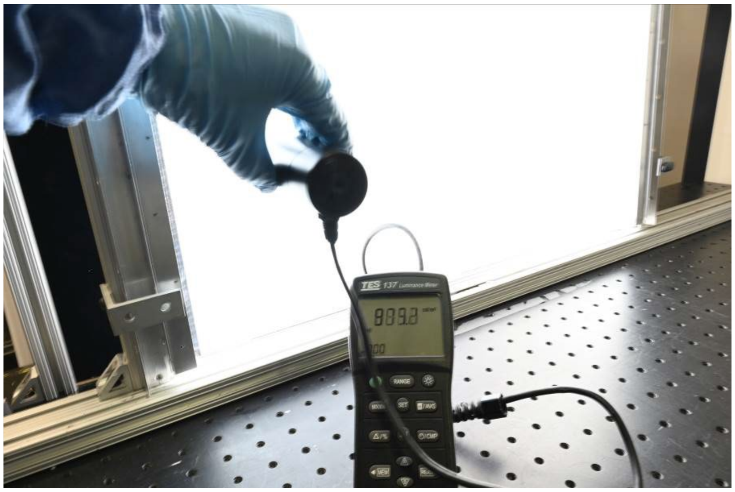
Source: Lucent Optics, Inc.

Optimizing the Patterning Process for Emission Uniformity and Maximum Light Output

The optimization of the patterning process was directed to balancing the uniformity of the emission produced by the microprinted waveguides with attempts to obtain as high light output and optical efficiency from the waveguides as practically possible. This presented certain challenges. Generally, increasing the light output from a waveguide requires higher densities of the microprinted pattern on its surface. This is needed to maximize the rate of light extraction and prevent light from leaking from edges of the waveguide. However, increasing the density of the light extraction pattern can also lead to a premature depletion of light in certain areas of the waveguide and the resulting loss of emission uniformity. This can often manifest itself in the appearance of relatively dark areas in the middle of the panel or at its edges. Therefore, the optimization process included measuring the actual intensity distributions produced by the experimental waveguides and adjusting the optical models and the microprinting process to maximize both the uniformity and light output.

The uniformity of light emission produced by the patterned waveguiding substrates was evaluated using two different methods. One method included spot luminance measurements at different locations of the substrate's surface and the other method involved high dynamic range imaging (HDRI). The waveguides were illuminated using the low-profile LED strip engines developed earlier. For spot luminance measurements (Figure 26), the project team used a luminance meter having a 2° measurement angle with about 20-mm aperture and having a spectral sensitivity calibrated according to the CIE 1931 luminosity function with an absolute accuracy of ±3 percent.

Figure 26: Spot Luminance Measurements of LED-illuminated Waveguiding Substrate



Source: Lucent Optics, Inc.

For HDRI measurements (Figure 28), a mirrorless DSLR-grade digital camera with a high-resolution CMOS sensor and RAW (unprocessed) picture capturing capability was used. The camera was calibrated through a series of experiments involving highly diffuse surfaces, actual 2ft x 2ft lighting panels with known light output, and spot control measurements of the surface brightness using the luminance meter mentioned. The calibration further included identifying the sensitivity range in which the camera's CMOS sensor has the maximum linearity and adjusting the exposure so that the photon count was always within that range during the measurements. Since vignetting effects may potentially impact the accuracy of the measurements near image edges, these effects were also taken into account during the calibration.

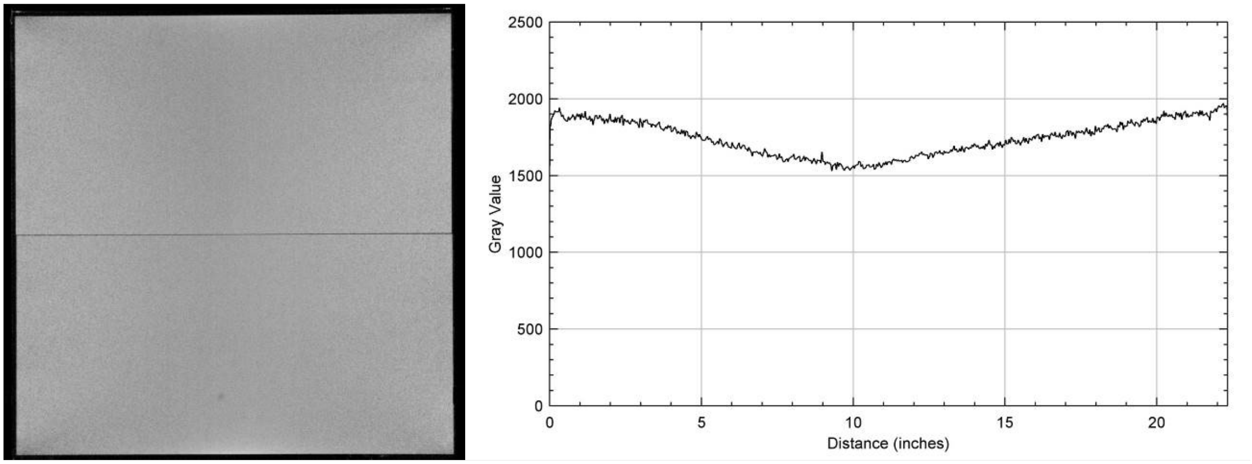
Figure 27: Test Bench for Assessing Uniformity of Lighting Panel Prototypes (left) and HDRI Measurements of the LED-illuminated Panel (right)

Source: Lucent Optics, Inc.

The HDRI data were initially captured in the form of a gray-scale RAW image which was then processed to extracts an intensity-profiles across the panel (Figure 28). The intensity profile represented gray pixel values tabulated according to the camera resolution and selected spatial averaging intervals. The gray pixel values were then converted into luminous intensity values using reference measurements performed using the spot luminance meter.

When significant discrepancies between the model and experiment were identified, the actual luminance profiles were used to further refine controlling parameters in the optical model and also update key processing parameters of UV microprinting. The process was iteratively repeated until the discrepancies were statistically insignificant or at most within 5-10 percent from the mean value. Furthermore, this iterative model verification process was also applied to a wide range of dimensions and thicknesses of the patterned substrates to ensure that the model can be used for generating light extraction patterns and predicting the waveguide performance for different configurations of lighting products.

Figure 28: Results of HDRI Measurements used for Refining the Optical Model and UV Microprinting Process



Left: raw gray-scale digital image. Right: measured pixel intensity profile.

Source: Lucent Optics, Inc.

As a result of the pattern generation and microprinting process optimization, brightness uniformity of above 90 percent has been achieved for most experimental panels, up to the size of 2′x4′. This compares well to the fluorescent and LED troffers which emission is typically either non-uniform or has uniformity below 80 percent.

The light extraction efficiency was evaluated by measuring both the light output from the surface of the substrate and the residual light energy emitted from an edge opposite to the LEDs. It was determined that the light extraction efficiency ranges from 90 percent to 95 percent for substrates patterned for single-sided light input and from 95 percent to 98 percent for two-sided light input. Accordingly, it can be concluded that the two-sided light input can be preferred when the application requires maximizing the light output and system efficacy. On the other hand, the difference in the light extraction efficiency for the one-sided input is fairly small compared to the optical losses occurring in conventional wide-area luminaires. Therefore, waveguiding substrates with one sided light input could still be considered for high performance applications, especially considering their design convenience and lower cost potential compared to their two-sided counterparts.

At the above light extraction efficiencies, overall luminaire-level optical efficiencies in the range from 84 percent to 88 percent can be expected for the fully assembled CoreGLO lighting fixtures employing thin and flexible waveguides patterned using the UV microprinting technology. This compares well to the standard 70-80 percent optical efficiency expectation of state-of-the-art mainstream commercial lighting troffers and 80-85 percent optical efficiencies of some LED troffers in a high-performance product category, none of which providing thin and flexible forms and material efficiency comparable to CoreGLO panels.

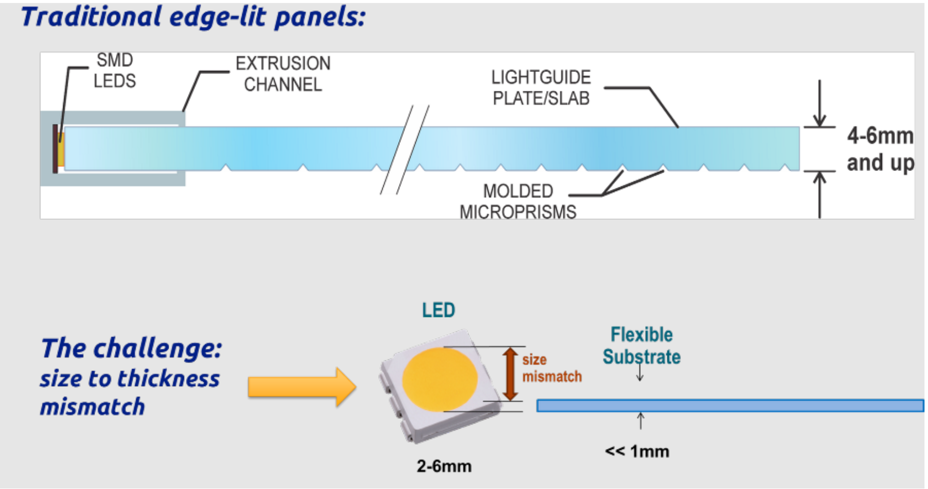
CHAPTER 7:
Light Coupling Optics Development

General Design Considerations and Identifying Improvement Pathways for Light Coupling

The main purpose of light coupling optics is to minimize optical losses when pairing relatively large high-brightness LEDs to thin and flexible light guiding substrates. The use of such optics is particularly important for the configurations of CoreGLO panels where the thickness of the light guiding substrate is less than the size of the respective edge-coupled LED packages. In these cases, properly designed light coupling optics can significantly enhance the utility and energy efficiency of the thin and flexible LED lighting panels, as well as reduce the cost and improve the overall and utility of the panels.

The principal challenge associated with the efficient coupling of “oversized” LED packages to ultra-thin substrates is illustrated below in Figure 29. In a conventional edge-lit lighting panel employing a rigid light guiding plate (LGP), the thickness of the plate typically exceeds the size of the respective LED package. This is necessary to allow most of the light emitted by the LEDs to enter the plate through its edge. However, to achieve the desired ultra-thin form factor and flexibility of the panel, the thickness of the waveguide has to be reduced by several times. This can create a mismatch between the LED size and the thickness of the waveguide. The size mismatch can leave parts of the light emitting surface of the LED uncovered by the waveguide’s edge and ultimately lead to a significant light spillage, hence reducing the energy efficiency of the lighting panel.

Figure 29: Illustration of the Challenges Related to Efficient Coupling of Conventional LED Packages to Ultra-thin/Flexible Light Guiding Substrates



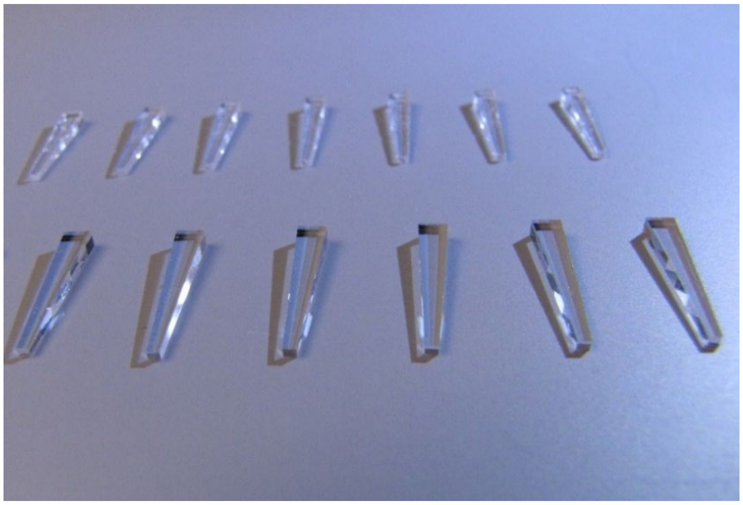
Source: Lucent Optics, Inc.

To solve the arising size/thickness mismatch problem, Lucent Optics has previously introduced waveguiding structures with light coupling optics that can recover much of the spilled light and guide it back into the waveguide. In this project, the work included further development of the light coupling optics and identifying pathways for further improving their optical design and light coupling efficiency. The project team evaluated and prioritized the main technical requirements for the optical couplers to ensure their compatibility with the material of the flexible light guides, minimize the chance of light spillage at the coupler/substrate optical interfaces, and simplify lighting panel manufacturing.

The team further experimented with various techniques to obtain an acceptably low surface roughness for the optical couplers. The optimal selection of surface finish was found to be important in two different aspects. On one hand, the roughness should be as low as possible since the couplers must efficiently reflect light using the so-called Total Internal Reflection (TIR) mechanism. A mirror-like surface finish is generally required to enable TIR. On the other hand, it was determined that producing light couplers economically using conventional manufacturing techniques and, on a scale required for general lighting may be unfeasible when setting the surface roughness parameters to the highest available optical standards. Furthermore, by working with the vendors selected to provide rapid prototyping and injection molding services to produce the optical couplers, it was determined that defining the mold parameters should preferably be made according to the industry standards of the Society of the Plastics Industry (SPI).

In order to find the right balance between the optical performance and manufacturing cost, several experimental light couplers with different surface finishes were produced (Figure 30). The performance of the couplers was evaluated to down-select the desired surface finishing process which should be required from injection molding vendors. The SPI-A1 surface finish/process was finally selected as the performance target for the surface quality of the optical couplers for the subsequent prototyping.

Figure 30: Selection of Experimental Optical Couplers Produced With Different Surface Finishes



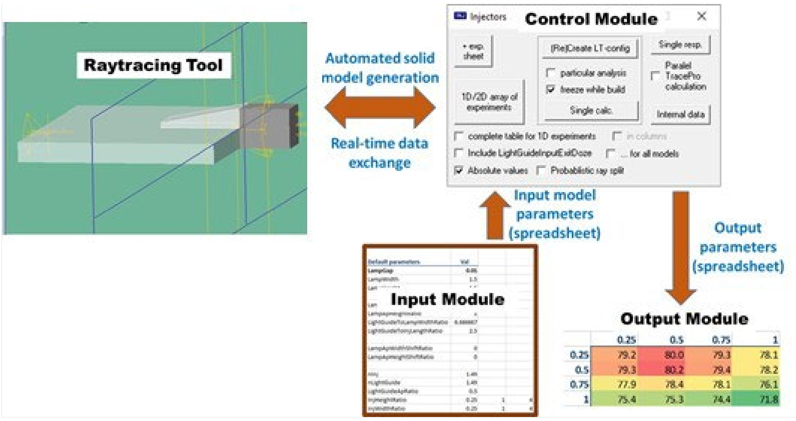
Source: Lucent Optics, Inc.

Material Selection and Design Optimization

The work further included experimenting with different materials and finalizing the optical couplers' material based on the estimated best cost-to-performance ratios. Besides the optical transmittance, other parameters of the materials which were found to be playing a significant role in the light injection efficiency of the couplers include the optical density (which is characterized by a refractive index of respective material) and the overall geometry of each coupler.

The design of optical couplers was optimized using ray tracing and iterative model modifications to achieve the targeted performance parameters. For this purpose, the project team used Lucent Optics' proprietary computer software that performs raytracing and optimization of light coupling optics, allowing for iterative modification of the optical model and conducting raytracing analysis in a semi-automated regime. This software also provides the capabilities to interface with state-of-the-art commercial raytracing tools and allows for independently verifying the results using such tools. A basic schematic of the modeling software is illustrated in Figure 31. The optimization control algorithms employed in this software provided the project team with the ability to define system parameters that should have fixed values and also the parameters that need to be optimized.

Figure 31: Schematics and Screenshots of the Optical Modeling Software Used for the Design and Optimization of Optical Couplers



☐ particular analysis
☑ freeze while build
☐ Parallel TracePro calculation
☐ complete table for 1D experiments
☐ in columns
☐ Include LightGuideInputExitDoze
☐ ... for all models
☑ Absolute values
☐ Probabilistic ray split

	0.25	0.5	0.75	1
0.25	79.2	80.0	79.3	78.1
0.5	79.3	80.2	79.4	78.2
0.75	77.9	78.4	78.1	76.1
1	75.4	75.3	74.4	71.8

Source: Lucent Optics, Inc.

In the optimization process, a large number of trial optical models were iteratively generated according to predefined ranges of set of control parameters. This was followed by running and storing logs of calculated performance parameters in a tabulated form. The project team analyzed the logs and chose the best-performing designs based on those calculations. For most of the models evaluated in this project, the team used simulations with 100,000 rays per each LED/coupler combination, which was deemed sufficient for making a preliminary selection of the optical coupler configurations. For the final comparison and down selection among several best design candidates of optical couplers, simulations were performed in a "high-fidelity" mode with up to 100,000 rays modeled for each candidate design to reduce the chance of error and increase the accuracy of performance parameter calculations.

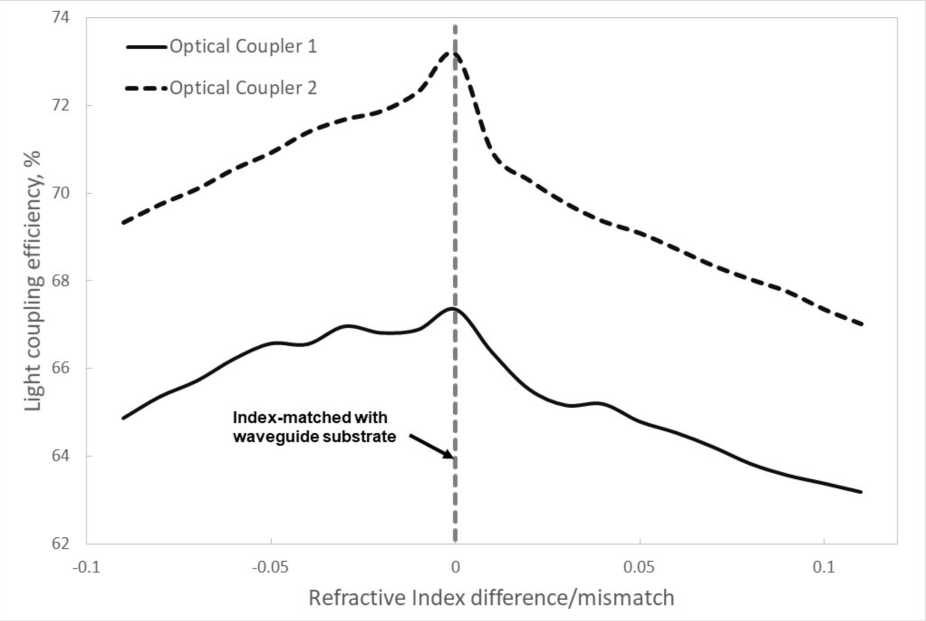
Besides enhancing the optical efficiency of LED coupling to thin and flexible waveguides, other factors considered in this optimization process included the manufacturability and future production cost. To aid this process, the project team also conducted a design tolerance analysis including dimensional errors of light couplers and LED positioning errors.

The design optimization process further included studies of the impact of the refractive index mismatch between the optical couplers and the underlying light guiding substrate which is used to redistribute and emit light from the LED panel. This required conducting optical raytracing experiments for selected configurations of light couplers and for different combinations of the refractive indices of the couplers and light guiding substrate. In each of the raytracing experiments, the total amount of energy injected into the light guiding substrate was determined and the total light coupling efficiency was calculated. For this task, the total light coupling efficiency was defined as a ratio between the amount of light injected into the light guiding substrate and the total amount of light emitted by the LEDs.

The obtained data were used for plotting the dependences of the light coupling efficiency from the difference in the refractive indices for different designs of light couplers. The resulting plots were used to determine the sensitivity of the light coupling efficiency on the refractive index mismatch and estimating the impact of this mismatch for various materials considered for the subsequent prototyping.

Figure 32 depicts exemplary dependences of the light coupling efficiency from the difference in the respective refractive indices for two different designs of light couplers. Both of those optical couplers were designed to inject light from a 3mm LED to a 1mm light guiding substrate, making about 3:1 LED size to waveguide thickness ratio.

Figure 32: Dependence of Light Coupling Efficiency on Refractive Index Mismatch Between the Waveguide Substrate and the Optical Couplers



Source: Lucent Optics, Inc.

Simple geometrical estimates for light input through a waveguide's edge suggest that, without the light couplers, the optical efficiency would have been less than 30 percent. In contrast, both studied designs demonstrate a significantly improved light coupling compared to the 30 percent reference case, providing about 67 percent and 73 percent efficiency, respectively.

Yet, it can also be seen that the performance is dependent on how closely the refractive indices match to each other. The peak performance is observed only at the points where there is a near-perfect index match. A gradual decline in the performance can be seen as the refractive index difference/mismatch increases in either positive or negative direction. For example, at a relatively small difference of only 0.1, the drop in light coupling efficiency attributed to the refractive index mismatch can be as large as 3-4 percent. While this energy loss does not impact the overall system operability and is not necessarily prohibitive from the total system efficiency prospective, the provided example illustrates that it is imperative to design the system such that the avoidable losses are minimized. In view of these results and considerations, the material selection choices were further narrowed to maximize the light coupling efficiency and the overall optical performance.

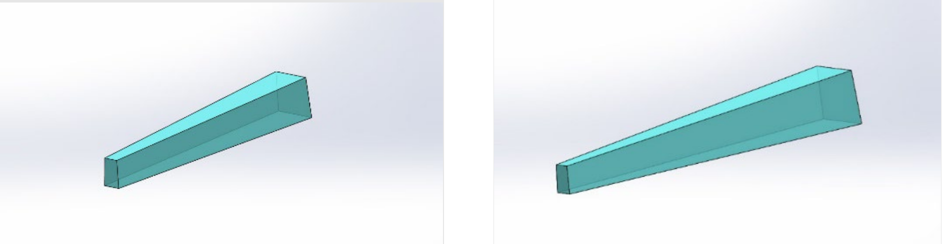
Addressing Design for Manufacturing Issues

A preferred way of implementing light coupling considered for prototyping in this project involved making the optical couplers separately from the light guiding substrate and then bonding them to the substrate near its light input edge using an index matched adhesive. Based on material research and the experiments described above, several candidate adhesive materials were identified. Further experiments also included determining various characteristics of the candidate materials which are relevant to both performance and manufacturing. These characteristics particularly included the optical transmittance, refractive index in the fully cured state, and the suitability of the adhesive material for reliably filing all of the air gaps between the light guiding substrate and optical couplers for providing a durable, monolithic structure, which is particularly important for developing a robust and scalable manufacturing process for the CoreGLO lighting panel.

Once the adhesive material had been identified, the design of the optical couplers was further refined based on the selected manufacturing method. Compared to the baseline light coupling technology, the new couplers provide several important improvements. The improvements particularly include a higher light coupling efficiency with a reduced light spillage, in part due to a better fit of the couplers to the LED packages used in the most recent LED engines, as well as providing more process choices for attaching the couplers to the light guiding substrate. The latter improvement is particularly important for reducing potential bottlenecks in the overall fabrication process of thin and flexible LED lighting panels employing "oversized" LEDs. The new couplers are also expected to help make the mechanical and optical connection of the couplers and the light guiding substrate more reliable and resilient to applying the external forces compared to the previous designs. This improvement is also important for ensuring the integrity of the panel during its flexing, installation and service.

The work further included pilot-prototyping the new design of optical couplers using injection molding and verifying the feasibility of the selected manufacturing approach. For this purpose, solid models for two different designs of the couplers, which were tailored to the two types of LED packages used in the LED engines, were created and an experimental injection molding tooling set was manufactured for making prototype couplers of these designs. The manufacturing tolerances of the tooling were constrained according to earlier findings, including SPI-A1 surface finish/process. A first batch of experimental optical couplers of both designs was injection molded using the developed tooling. The results of the preliminary prototyping were found satisfactory and the findings from testing the proof-of-concept optical couplers were used to finalize the couplers' design and fabrication process.

Figure 33: Solid Models of Optical Couplers Selected for Initial Prototyping



Source: Lucent Optics, Inc.

Figure 34: Experimental Couplers of the Newly Developed Designs Made Using Injection Molding

Source: Lucent Optics, Inc.

Establishing Pilot-Scale Manufacturing of Optical Couplers

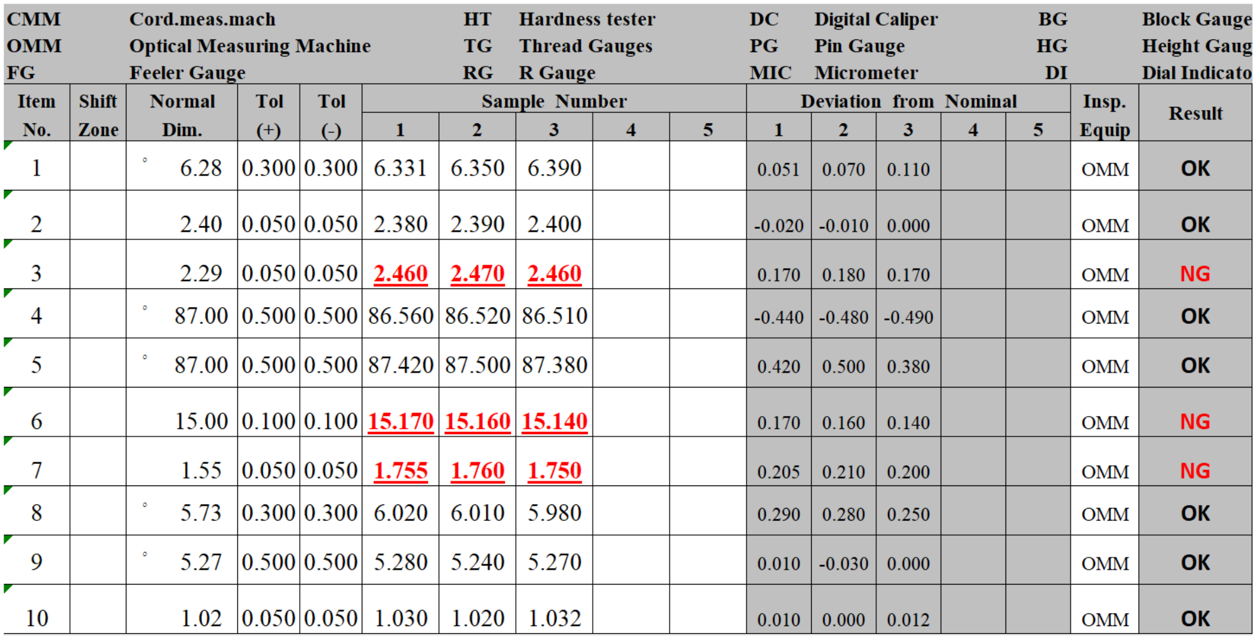
Based on the results of the above experiments, target optical performance and the selected technique for attaching the couplers to the flexible light guiding substrates, the project team finalized the overall approach for designing optical couplers and then used this approach to design two specific models of optical couplers which could be incorporated into CoreGLO panels employing different LED packages without the need of further development and re-tooling. The first model was designed for relatively small LED packages in the 2mm-2.5mm range, and the second model was designed for mid-size LED packages in the 3mm-3.5mm range.

Engineering drawings were created and sent to a competitively selected outside injection molding vendor for evaluation and making the appropriate custom tooling and molds. Minor subsequent design modifications for the couplers were iteratively performed based on the input from the vendor and to make the designs more compatible with the high-throughput injection molding process. More specifically, the locations of the gate and ejector pins, and parting lines have been adjusted and the requirements for the surface quality and dimensional tolerances have been updated. Furthermore, a detailed wall thickness analysis of the mold cavity to determine potential sink risks was performed. A draft analysis was also done to ensure that the part will release smoothly from the tool. All this information was used to create the full mold design.

As the designs of the parts and the mold cavity had been finalized and the necessary tooling fabricated from heat-treated mold steel, a trial injection molding production was run using a high-clarity PMMA plastic material. In this process, granular PMMA plastic was fed into a heated chamber where it was melted. The molten plastic was then forced through a nozzle into the respective steel mold cavity through a gate and runner system. Once the cavity was filled, a holding pressure was maintained to compensate for material shrinkage until the plastic fully solidified. The mold was then open and the solidified plastic part was then ejected, resulting in a finished optical coupler. The process was then repeated until a necessary quantity of coupler samples was made. A total of three samples of each of the coupler models were initially produced.

The produced samples were evaluated using a visual inspection and also using various specialized equipment. The dimensional and angular parameters were measured directly using an optical measuring machine (OMM) and digital calipers (DC). A total of ten different parameter measures were used to characterize the manufactured samples, including five dimensional parameters and five angular parameters. Table 4 summarizes the results of the measurements for the first model of optical couplers fabricated in this trial production run.

Table 5: Measurement Results for the First Model of Optical Couplers



CMM	**Cord.meas.mach**	**HT**	**Hardness tester**	**DC**	**Digital Caliper**	**BG**	**Block Gauge**
OMM	**Optical Measuring Machine**	**TG**	**Thread Gauges**	**PG**	**Pin Gauge**	**HG**	**Height Gaug**
FG	**Feeler Gauge**	**RG**	**R Gauge**	**MIC**	**Micrometer**	**DI**	**Dial Indicato**

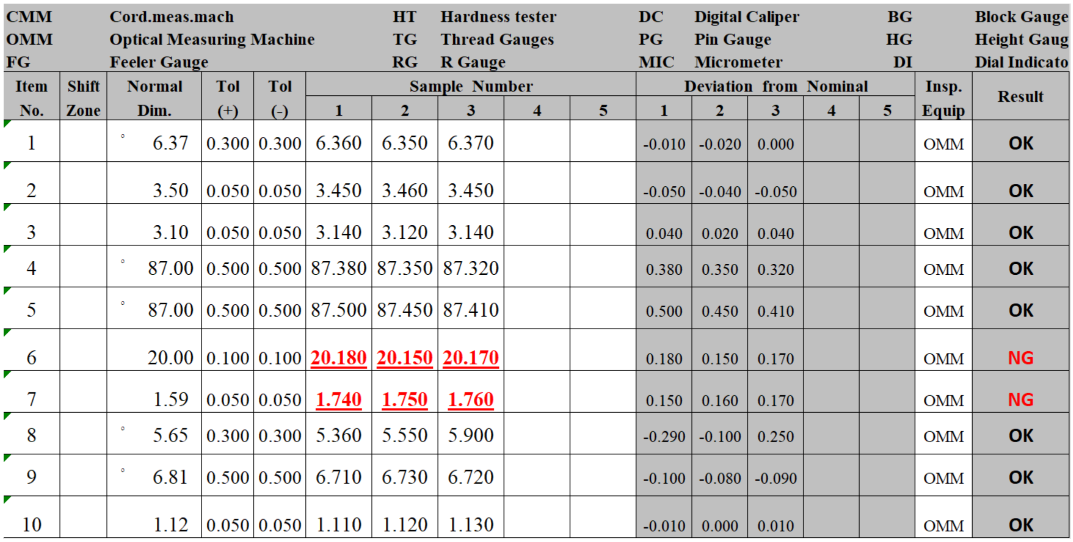
Item No.	Shift Zone	Normal Dim.	Tol (+)	Tol (-)	Sample Number 1	2	3	4	5	Deviation from Nominal 1	2	3	4	5	Insp. Equip	Result
1		° 6.28	0.300	0.300	6.331	6.350	6.390			0.051	0.070	0.110			OMM	OK
2		2.40	0.050	0.050	2.380	2.390	2.400			-0.020	-0.010	0.000			OMM	OK
3		2.29	0.050	0.050	2.460	2.470	2.460			0.170	0.180	0.170			OMM	NG
4		° 87.00	0.500	0.500	86.560	86.520	86.510			-0.440	-0.480	-0.490			OMM	OK
5		° 87.00	0.500	0.500	87.420	87.500	87.380			0.420	0.500	0.380			OMM	OK
6		15.00	0.100	0.100	15.170	15.160	15.140			0.170	0.160	0.140			OMM	NG
7		1.55	0.050	0.050	1.755	1.760	1.750			0.205	0.210	0.200			OMM	NG
8		° 5.73	0.300	0.300	6.020	6.010	5.980			0.290	0.280	0.250			OMM	OK
9		° 5.27	0.500	0.500	5.280	5.240	5.270			0.010	-0.030	0.000			OMM	OK
10		1.02	0.050	0.050	1.030	1.020	1.032			0.010	0.000	0.012			OMM	OK

Source: Lucent Optics, Inc.

All of the angular parameters and two out of five dimensional parameters of the produced optical couplers were found to be within the established tolerances from the design specifications. Also, the consistency of the measured parameters was very good between all three samples. However, three dimensional parameters were slightly outside the acceptable ranges. These are marked with a red color and “NG” in the results column.

Similarly, measurements of the optical couplers of the second model (Table 5) has also demonstrated a generally good conformance to the specifications. The cross-sample difference generally did not exceed several micrometers for dimensional parameters and 0.2 degrees in angular parameters. Yet, two out of five dimensional parameters fell outside the acceptable range by several hundred micrometers. While these deviations from the designed parameters appear to be rather small compared to the respective dimensions, they were nevertheless deemed material for the purpose of validating the optical models with sufficiently high confidence.

Table 6: Measurement Results for the Second Model of Optical Couplers



CMM	**Cord.meas.mach**	**HT**	**Hardness tester**	**DC**	**Digital Caliper**	**BG**	**Block Gauge**
OMM	**Optical Measuring Machine**	**TG**	**Thread Gauges**	**PG**	**Pin Gauge**	**HG**	**Height Gaug**
FG	**Feeler Gauge**	**RG**	**R Gauge**	**MIC**	**Micrometer**	**DI**	**Dial Indicato**

Item No.	Shift Zone	Normal Dim.	Tol (+)	Tol (-)	Sample Number					Deviation from Nominal					Insp. Equip	Result
					1	2	3	4	5	1	2	3	4	5		
1		° 6.37	0.300	0.300	6.360	6.350	6.370			-0.010	-0.020	0.000			OMM	OK
2		3.50	0.050	0.050	3.450	3.460	3.450			-0.050	-0.040	-0.050			OMM	OK
3		3.10	0.050	0.050	3.140	3.120	3.140			0.040	0.020	0.040			OMM	OK
4		° 87.00	0.500	0.500	87.380	87.350	87.320			0.380	0.350	0.320			OMM	OK
5		° 87.00	0.500	0.500	87.500	87.450	87.410			0.500	0.450	0.410			OMM	OK
6		20.00	0.100	0.100	**20.180**	**20.150**	**20.170**			0.180	0.150	0.170			OMM	NG
7		1.59	0.050	0.050	**1.740**	**1.750**	**1.760**			0.150	0.160	0.170			OMM	NG
8		° 5.65	0.300	0.300	5.360	5.550	5.900			-0.290	-0.100	0.250			OMM	OK
9		° 6.81	0.500	0.500	6.710	6.730	6.720			-0.100	-0.080	-0.090			OMM	OK
10		1.12	0.050	0.050	1.110	1.120	1.130			-0.010	0.000	0.010			OMM	OK

Source: Lucent Optics, Inc.

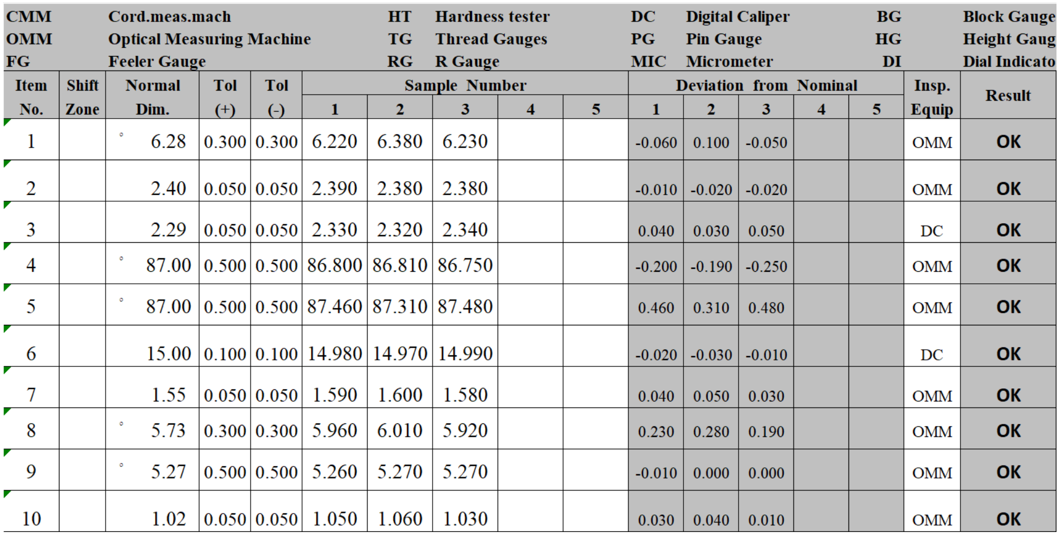
To address the remaining deviations of injection molded optical couplers from the design requirements, the project team worked with the vendor to further refine the tooling and iteratively produce samples which would fully conform to the specifications. This process involved a mold flow analysis using various analytical tools. A particular focus was placed on fill pattern, sheer stress, weld lines, and potential air pockets.

Using the fill pattern analysis, the areas of the mold cavity which are difficult of fill or could even result in no-fill conditions were identified. This, in turn, helped optimize the number, size, and location of the gates into the molded parts. The sheer stress analysis was used to identify areas of elevated residual stresses in the injection molded parts where cracks or unwanted warps in the finished parts could occur. Finally, the flow pattern was used to identify areas of the mold cavity that are last to fill with the molten PMMA and redesigning the cavity to allow all the trapped air to escape from the mold.

The injection molding tooling was updated based on the analysis findings and a second trial production run was performed using the updated tooling. The produced samples were evaluated using the same measurement process and equipment. The results of the measurements are shown in Tables 6 and 7.

As the new measurements indicate, all of the dimensional parameters of the second batch of samples were within the design specifications. Accordingly, the improved mold cavity was deemed of sufficient quality and selected for the subsequent full production run.

Table 7: Measurement Results for the First Model of Optical Couplers Produced with the Improved Mold Cavity

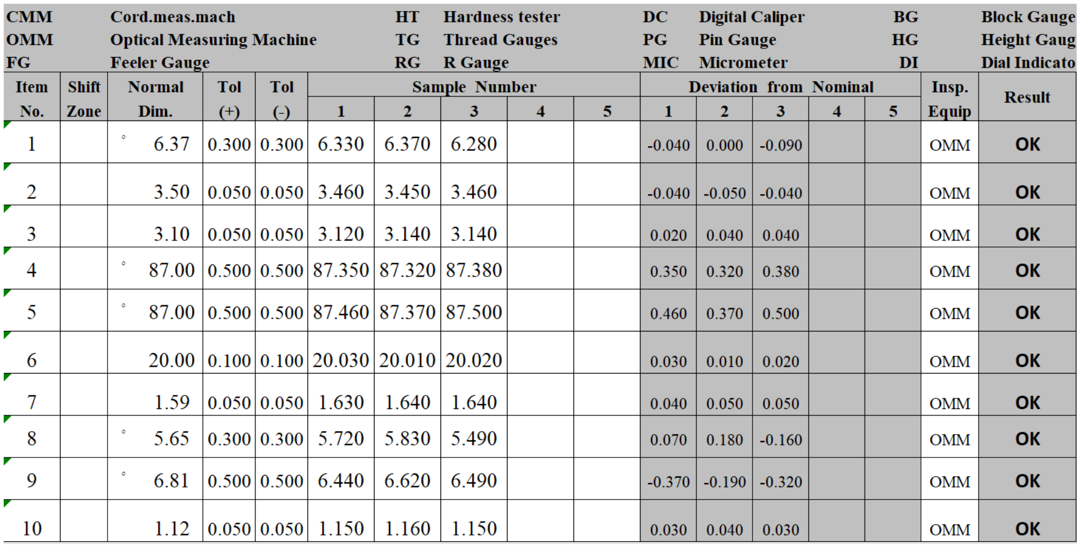


CMM	Cord.meas.mach	HT	Hardness tester	DC	Digital Caliper	BG	Block Gauge
OMM	Optical Measuring Machine	TG	Thread Gauges	PG	Pin Gauge	HG	Height Gaug
FG	Feeler Gauge	RG	R Gauge	MIC	Micrometer	DI	Dial Indicato

Item No.	Shift Zone	Normal Dim.	Tol (+)	Tol (-)	Sample Number					Deviation from Nominal					Insp. Equip	Result
					1	2	3	4	5	1	2	3	4	5		
1		° 6.28	0.300	0.300	6.220	6.380	6.230			-0.060	0.100	-0.050			OMM	OK
2		2.40	0.050	0.050	2.390	2.380	2.380			-0.010	-0.020	-0.020			OMM	OK
3		2.29	0.050	0.050	2.330	2.320	2.340			0.040	0.030	0.050			DC	OK
4		° 87.00	0.500	0.500	86.800	86.810	86.750			-0.200	-0.190	-0.250			OMM	OK
5		° 87.00	0.500	0.500	87.460	87.310	87.480			0.460	0.310	0.480			OMM	OK
6		15.00	0.100	0.100	14.980	14.970	14.990			-0.020	-0.030	-0.010			DC	OK
7		1.55	0.050	0.050	1.590	1.600	1.580			0.040	0.050	0.030			OMM	OK
8		° 5.73	0.300	0.300	5.960	6.010	5.920			0.230	0.280	0.190			OMM	OK
9		° 5.27	0.500	0.500	5.260	5.270	5.270			-0.010	0.000	0.000			OMM	OK
10		1.02	0.050	0.050	1.050	1.060	1.030			0.030	0.040	0.010			OMM	OK

Source: Lucent Optics, Inc.

Table 8: Measurement Results for the Second Model of Optical Couplers Produced with the Improved Mold Cavity



CMM	Cord.meas.mach	HT	Hardness tester	DC	Digital Caliper	BG	Block Gauge
OMM	Optical Measuring Machine	TG	Thread Gauges	PG	Pin Gauge	HG	Height Gaug
FG	Feeler Gauge	RG	R Gauge	MIC	Micrometer	DI	Dial Indicato

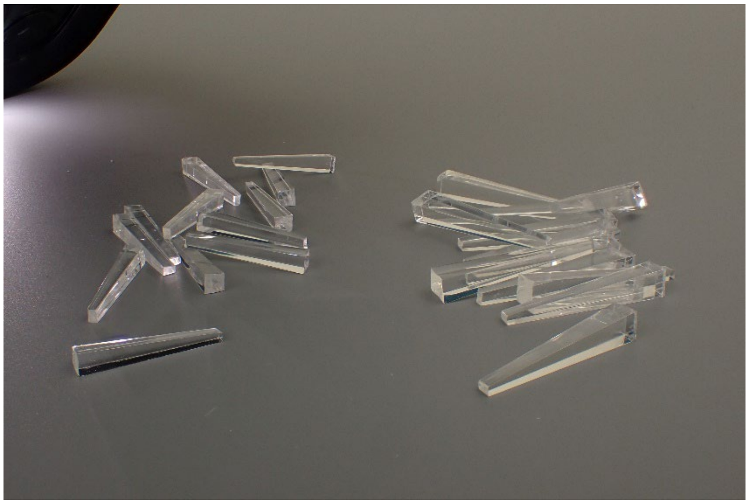
Item No.	Shift Zone	Normal Dim.	Tol (+)	Tol (-)	Sample Number					Deviation from Nominal					Insp. Equip	Result
					1	2	3	4	5	1	2	3	4	5		
1		° 6.37	0.300	0.300	6.330	6.370	6.280			-0.040	0.000	-0.090			OMM	OK
2		3.50	0.050	0.050	3.460	3.450	3.460			-0.040	-0.050	-0.040			OMM	OK
3		3.10	0.050	0.050	3.120	3.140	3.140			0.020	0.040	0.040			OMM	OK
4		° 87.00	0.500	0.500	87.350	87.320	87.380			0.350	0.320	0.380			OMM	OK
5		° 87.00	0.500	0.500	87.460	87.370	87.500			0.460	0.370	0.500			OMM	OK
6		20.00	0.100	0.100	20.030	20.010	20.020			0.030	0.010	0.020			OMM	OK
7		1.59	0.050	0.050	1.630	1.640	1.640			0.040	0.050	0.050			OMM	OK
8		° 5.65	0.300	0.300	5.720	5.830	5.490			0.070	0.180	-0.160			OMM	OK
9		° 6.81	0.500	0.500	6.440	6.620	6.490			-0.370	-0.190	-0.320			OMM	OK
10		1.12	0.050	0.050	1.150	1.160	1.150			0.030	0.040	0.030			OMM	OK

Source: Lucent Optics, Inc.

A full production run was performed using the same process parameters and about two hundred couplers of each type were produced. A photograph of representative optical couplers of both types from this production is shown Figure 35.

A visual inspection and measurements of dimensional parameters from randomly sampled couplers of the production batch have shown a good consistency among samples and repeatability of the manufacturing process, indicating that the pilot manufacturing of optical couplers designed for LED custom size (such as LED packaged sized in 2mm-2.5mm and 3mm-3.5mm range) can be considered established.

Figure 35: Optical Couplers Made Using the Full-production Run

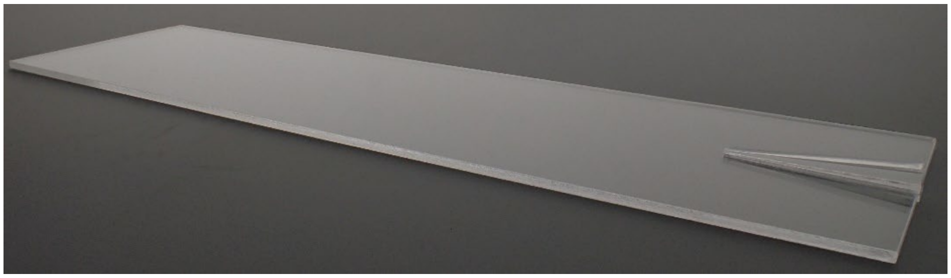


Source: Lucent Optics, Inc.

Evaluating the Performance of Optical Couplers

Several randomly selected optical couplers were further tested in a simulated operating environment. The goal was to assess the light coupling efficiency and verify that the developed couplers can significantly reduce optical losses compared to the case when no couplers are used. For this purpose, an individual optical coupler was mounted to a rectangular piece of unpatterned flexible waveguide substrate using an index-matched adhesive and illuminated by a collimated laser light source with stabilized light output.

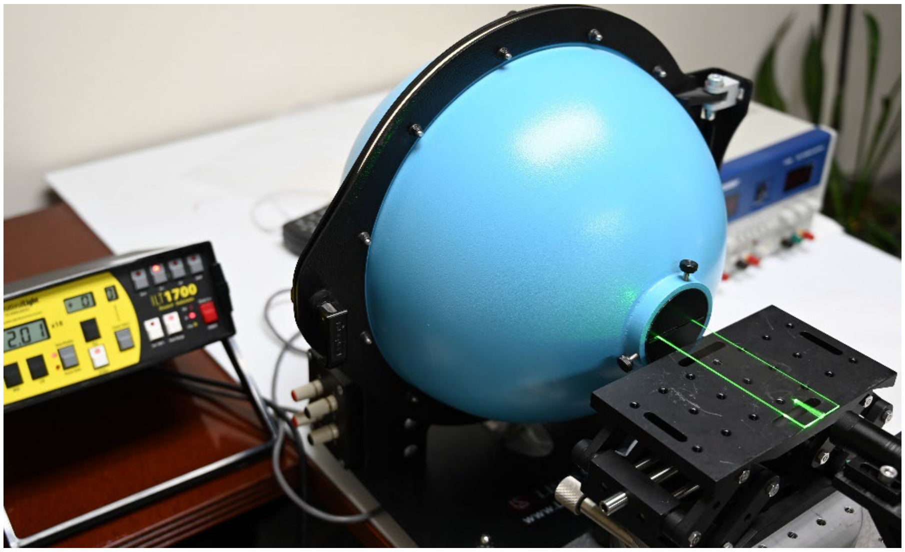
Figure 36: Individual Optical Coupler Mounted to Waveguide Substrate Using Index-matched Adhesive



Source: Lucent Optics, Inc.

The light emission produced by the source was further conditioned using beam expanding optics to produce a moderately collimated light beam which diameter approximated the size of the LED source for which the optical coupler had been optimized. The opposite end of the waveguide substrate was gently sanded to induce light extraction and inserted into an integrating sphere equipped with a light intensity meter. The light intensity produced within the integrating sphere was compared to the baseline light intensity in that sphere obtained using a reference waveguide substrate which was illuminated by the same light source but had no optical coupler on it.

Figure 37: Test Setup Used for Assessing the Performance of Optical Couplers



Source: Lucent Optics, Inc.

The measurements indicated that the light input into the waveguide increased by more than 200 percent, on average, for the case where the optical couplers were used, compared to the light input directly into a bare waveguide. This result is in line with the expectations based on optical modeling and demonstrates that most of the optical losses attributed to the mismatch between the relatively large size of the employed LED packages and the relatively low thickness of the flexible waveguiding substrate are rescued using the current optical coupler's design. Accordingly, the detailed analysis of the produced samples, including dimensional, surface quality and optical performance tests, confirms that the developed optical couplers reduce the LED/waveguide light coupling losses by a considerable percentage compared to the case when no couplers are used. Therefore, the optical couplers of the new design can be incorporated into next-generation CoreGLO LED lighting panels for enhancing the overall energy efficiency of the panels when the LED size to waveguide thickness mismatch problem is present.

CHAPTER 8:
System Integration

Overall System-Level Optimization

The goal of the System Integration task was to design and fabricate commercial-size, fully functional ultra-thin and flexible LED lighting panel prototypes as well as assess their performance, addressing system-level optimization, electrical, thermal management, structural and installation issues. The project team particularly focused on designing and demonstrating prototypes of full-scale luminaires using the CoreGLO technology and some of its advancements developed in the previous tasks. The work also included optimizing the panel structure and further reducing the weight and raw materials intake by implementing a frameless design. A particular emphasis of this effort was minimizing the overall number of components and reducing the manufacturing costs and dependence on the potential supply chain issues.

As a result of this effort, a good progress was achieved in further reducing the overall material redundancy within the CoreGLO panels. This, in turn, allowed to reduce the weight and thickness of the panels, as well as reduce the number of optical layers and the overall intake of raw materials compared to the baseline design and without materially affecting the baseline performance. The sections below will discuss the results of this work and demonstrate several examples of the prototype luminaires designed and build using the ultra-thin and flexible CoreGLO panels.

LED Driver Selection

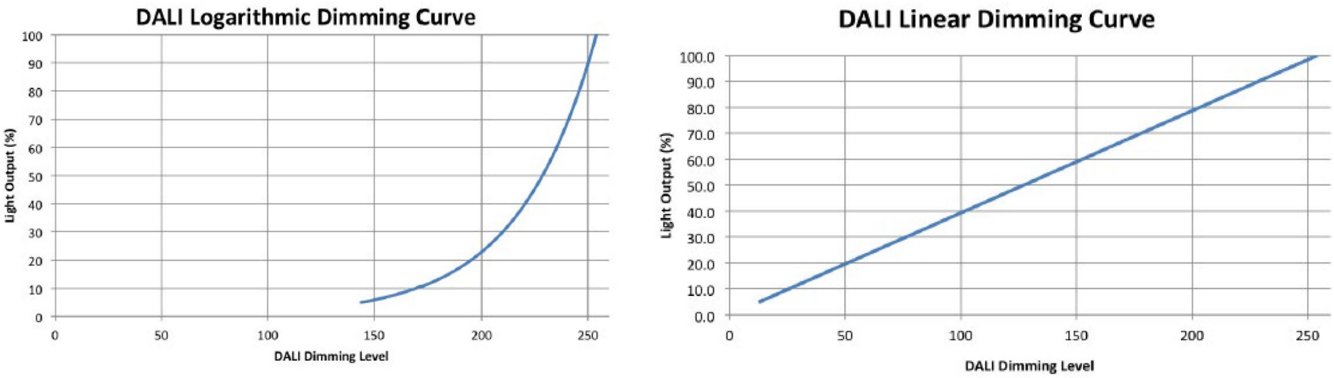
The development of power supplies for ultra-thin and flexible lighting panels was outside of the scope of this project. Instead, the project team focused on identifying and selecting off-the-shelf dimmable LED drivers suitable for powering the panels and, more specifically, the LED modules developed in previous tasks. The criteria used for LED driver selection particularly included the cost effectiveness, compactness, conformance to the current safety and performance regulations, and compatibility with intelligent light controls. Based on this preliminary selection, the project team acquired several models of commercially available LED drivers. The LED drivers were first tested for their conformance to the rated specifications and several candidates were discarded based on those tests. The suitability of the drivers for wireless connected lighting systems was determined based on the manufacturer-advertised specifications. However, no independent testing of that functionality was performed since it was outside of the scope of this project. The final down-selection of two different dimmable Class 2 models was based on the tests of the remaining drivers for their compatibility with the anticipated designs and application scenarios of the lighting luminaires considered for demonstrating the capabilities of the thin and flexible LED panels being developed. These LED drivers are depicted in Figure 38.

Figure 38: LED Drivers Selected for Final Prototyping and Lighting System Integration

Source: Lucent Optics, Inc.

A 40W LED driver provides a dimming range of 1 percent – 100 percent through the standard digital interface based on DALI 2.0 (IEC 62386) and uses an adjustable output current range from 0.1A to 1.1A to meet specified max output current and dimming range. Dimming curves for this driver are shown in Figure 39. In addition to the DALI interface, the driver can also be programmed using a wireless interface and using manufacturer-supplied software. The driver can be programmed both when it is not powered (in "offline" programming mode) and when it is powered (in "online" programming mode). These features are thought to make the target LED panels employing such drivers particularly suitable for connected systems and smart grid applications.

Figure 39: Typical Dimming Curves for DALI Logarithmic (left) and Linear (right)



Source: Lucent Optics, Inc.

Prototyping and Testing LED Panels for Different Lighting Fixture Sizes

The project team further designed, manufactured, and tested several LED lighting panel prototypes based on the improved CoreGLO technology. The panels were prototyped in four different sizes: 12″x48″, 24″x24″, 24″x48″, and 16″x32″. The first three sizes correspond to the respective dimensions of the standard troffer types that are used in commercial buildings, and the fourth one represents a custom size designated for architectural lighting applications. For testing purposes, each panel was attached to a metal frame which held the panel in a planar configuration during measurements. One of the finished panels in depicted in Figure 39.

Figure 40: Prototype of a 24”x48” CoreGLO LED Lighting Panel Prepared for Testing

Source: Lucent Optics, Inc.

Measurements of the emission uniformity of the panels were performed in-house using a calibrated luminance meter. Further detailed electrical and optical tests were performed by the same independent lab which was used for testing earlier prototypes. The third-party tests included measurements of the total luminous output from the panels as well as their efficacy and angular distribution of the emission using a type-C Goniophotometer in accordance with IES LM-79 (2019) protocol. Some of the key performance parameters of the prototype panels are summarized in Table 8 while the detailed photometric and electrical data, as well as visualization of the measured emission distributions, are available upon request.

Table 9: Measurement Results for the Second Model of Optical Couplers

Performance Parameter	Panel #1	Panel #2	Panel #3	Panel #4
Panel Size (light-emitting area)	48” x 12”	36” x 24”	36” x 32”	48” x 24”
Input Power (Watt)	74 W	36 W	47 W	73 W
Total Light Output (direct/indirect)	9,047 lm	4,437 lm	5,789 lm	9,006 lm
Total Light Output (direct)	8,678 lm	4,139 lm	5,493 lm	8,715 lm
Luminaire-level Efficacy (with two-sided emission)	122 lm/W	125 lm/W	124 lm/W	122.5 lm/W
Efficacy (with single-sided emission)	117 lm/W	120 lm/W	118 lm/W	119 lm/W
Emission Uniformity	>85%	~90%	~90%	~90%

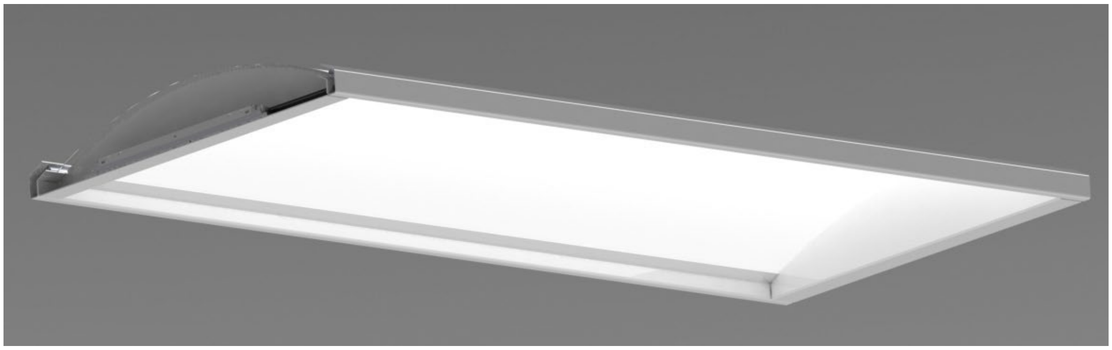
Source: Lucent Optics, Inc.

Flicker measurements were conducted in-house using a handheld ISO-certified flicker meter. These measurements have shown the percent flicker of 0.1-0.2 percent at the maximum luminance and 0.8 percent or less at the lowest point of the dimming range. For reference, percent flicker values of less than 5 percent are generally considered imperceptible to the human eye. For comparison, our tests of linear fluorescent fixtures and several types of replacement LED tubes (T-LEDs) have shown much higher percent flicker, ranging from 5 percent in the best cases and up to 30-35 percent in several other cases.

Volumetric LED Troffer Design

In this task, the project team focused on designing a demonstrational prototype of a full-scale volumetric LED lighting troffer using the CoreGLO technology which was further developed in this project. A solid model of the developed design is shown in Figure 41.

Figure 41: Solid Model of a Volumetric 2'x4' Lighting Troffer Using Ultra-thin Flexible LED Panel



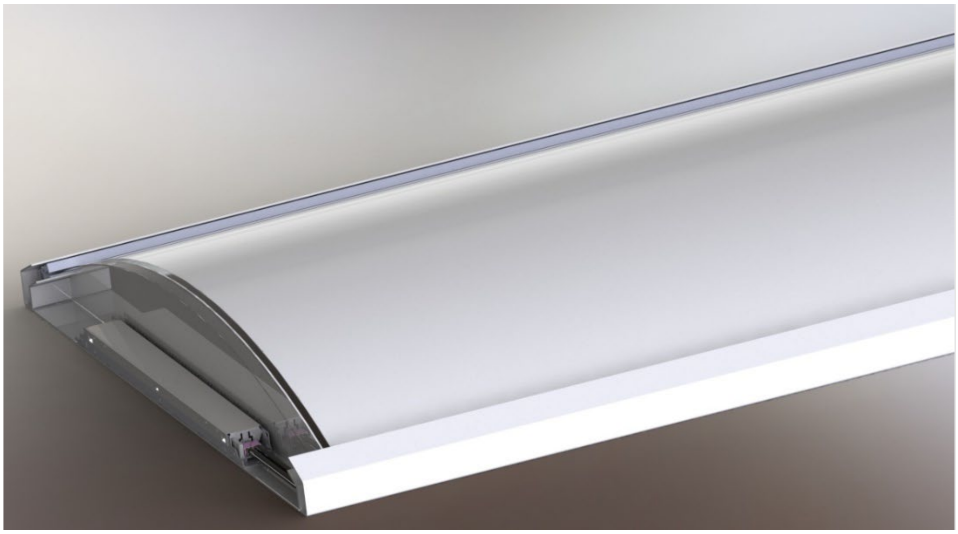
Source: Lucent Optics, Inc.

Compared to a conventional, flat-panel troffer design, the light-emitting panel of this troffer has an optimized structure in which the weight and raw materials intake are significantly reduced. The optimization particularly included reducing the thickness of the optical waveguide to about 1mm, reducing the dimensions of the LED engines and the intake of aluminum in the engine's housing, and reducing the number of optical layers in the panel with eliminating the need of an optical diffuser lens. A yet further reduction of the weight and materials use was achieved by implementing a frameless design for the panel.

The troffer was designed in a volumetric implementation in which the CoreGLO panel has a slight curvature and the light emitting body of the fixture has a concave, trough-like shape. This design is intended to soften and distribute light more evenly on high vertical surfaces within a space compared to a planar design. It should particularly allow for lowering the luminous contrast between the fixture and ceiling and promote filling the entire space with light, without glare or cave effect of traditional downlights, which can be especially useful in spaces that have many walls, cubicles, and work surfaces (such as typical workplaces such as offices).

In the developed troffer, the LED driver is secured to an outer surface of the troffer's side (Figure 42). This is an additional material-saving feature that eliminates the need for additional framing structures and hardware compared to conventional troffer panels. Compared to other volumetric designs used in traditional lighting and being generally more costly compared to the flat panels, the developed design retains the weight and cost reduction benefits of the ultra-thin and flexible LED panel. The volumetric quality of the troffer is formed by flexing the panel to a trough-like shape and fixing that shape in place using a pair of side walls with arcuate profiles.

Figure 42: Top View of the Troffer With a Side-mounted LED Driver



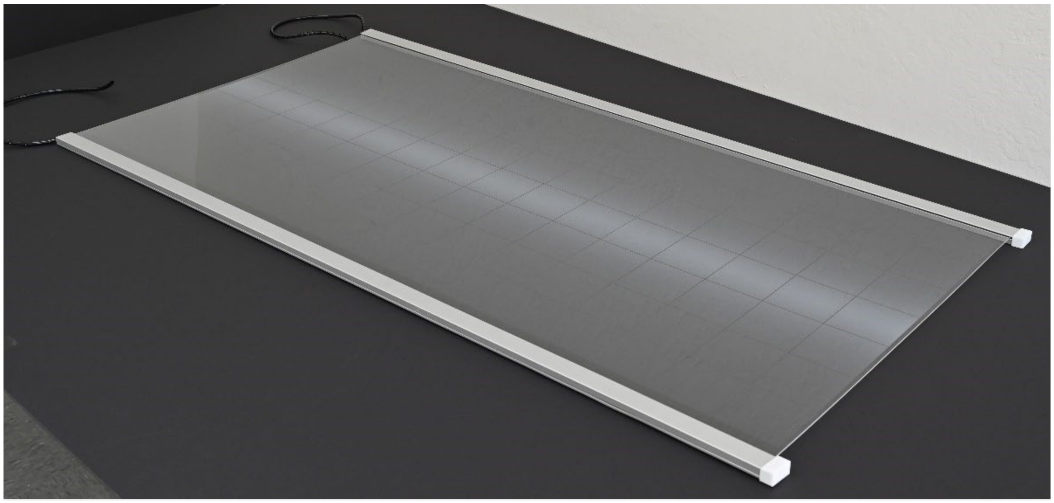
Source: Lucent Optics, Inc.

Prototyping the 2′x4′ Volumetric LED Troffer

The effort on prototyping the volumetric LED troffer was directed to not only demonstrating the capabilities and a practical implementation of the developed technology, but also to addressing potential mass production issues such as quality control, performance tests, certification tests, and manufacturing cycle duration. A particular emphasis of this effort was on reducing the manufacturing costs and raw materials intake in the panel while providing sufficient heat dissipation and stable optical and electrical performance. The project team further addressed developing cost-effective installation strategies for integrating flexible LED lighting panels into connected lighting systems and simple retrofit applications of conventional fluorescent and LED troffers.

Figure 43 shows a 2′x4′ flexible CoreGLO LED panel made for this prototype. The optical waveguide of this panel was patterned using Lucent Optics' proprietary microprinting technology. The project team developed a custom light extraction pattern for this prototype. This light extraction pattern includes square-shaped patterned areas arranged in rows and columns and separated from one another by narrow non-patterned areas. This arrangement was found advantageous for further enhancing the aesthetic appearance of the troffer while preserving a uniform light output. The total weight of the panel was measured at 4.4 lbs., which translates to about 0.5 lbs. per square foot of panel area.

Figure 43: Ultra-thin LED Lighting Panel Developed for the Volumetric LED Troffer



Source: Lucent Optics, Inc.

The project team further assembled a structural frame for the CoreGLO panel which included a pair of side walls with arcuate profiles to support the panel in a bent state. The assembly process was completed by inserting the panel into the frame, covering the LED panel with a diffuse reflector film, and attaching the LED diver to the frame’s body. Photographs of the finished volumetric LED troffer are shown in Figure 44 and Figure 45.

Figure 44: 2’x4’ Volumetric LED Troffer Employing Ultra-thin LED Lighting Panel Bent to a Curved Shape

Source: Lucent Optics, Inc.

Figure 45: Top/Side View of the Troffer

Source: Lucent Optics, Inc.

The LED engines used in the troffer were made using two types of LED packages, each emitting light at a Color Rendering Index (CRI) of 90+ but in a different Correlated Color Temperature (CCT). The LED packages of each CCT (2,700K and 5,000K, respectively) were interconnected with one another and wired into two separate electrical circuits. These circuits were connected to separate channels of the LED driver such that the intensity of the respective LEDs of different CCTs could be independently controlled to set a custom color of the emission using a remote. Accordingly, the volumetric LED troffer was made color-tunable in the entire 2,700K-5,000K CCTs range.

Evaluating the Troffer Prototype in Relevant Building Environment

The project team then installed the developed volumetric LED troffer prototype into the ceiling grid at the Lucent Optics' headquarters in Sacramento, California (Figure 46 and Figure 47). Two types of installation were tried. In the first test installation, a ceiling tile from the grid ceiling space was removed and replaced with the volumetric LED troffer panel. This was found to be a relatively simple process which is very similar to the drop-in recessed installation of the conventional fluorescent and LED troffers. In the second installation, the project team replaced one of the existing 2'x4' recessed fluorescent troffers with the developed LED troffer. Both these installations allowed the project team to test and further refine the installation protocols towards the making the process more straightforward and universal.

The installed protype was assessed visually and tested in different illumination regimes, including brightness dimming and fine-tuning of the color of the emission using a remote control. The intended operability and performance, including the emission uniformity, were further confirmed by measuring the luminance at different locations of the panel's surface. The total installed weight of the troffer was measured at 3.7 kg (approximately 8 lbs.), which represents about half of the weight of commercially available fluorescent and LED troffers of this size.

Figure 46: Volumetric LED Troffer Installed Into a Ceiling Grid in a Commercial Building

Source: Lucent Optics, Inc.

Figure 47: Installed Volumetric LED Troffer in a Switched-on State

Source: Lucent Optics, Inc.

Tubular Architectural Wall Sconce

The project team further designed and fabricated a prototype of the architectural wall sconce with color tunable emission using the developed technology. One of the goals of this effort was to further demonstrate the capabilities of the developed technology to support various innovative designs of lighting fixtures for general illumination which were either not possible of fairly difficult to implement before.

The prototyped wall sconce employs an ultra-thin and flexible LED lighting panel which is similar to that of the volumetric troffer but which is bent further round the same axis to the shape of a full cylinder. The color tunability was implemented using the same approach as in the volumetric troffer, specifically using LEDs with different CCTs controlled using two independent channels.

For this prototype, the team developed and utilized a different custom light extraction pattern compared to the volumetric troffer. This new pattern was selected to further emphasize the perception of volume and other aesthetic effects brought by the tubular shape and translucent appearance of the sconce. The protyped LED wall sconce was further tested in operation as a lighting fixture and has shown an exceptional emission uniformity and a stable performance. Photographs of the prototype both in non-illuminated and illuminated states are shown in Figure 48.

Figure 48: Working Prototype of a Tubular Architectural Wall Sconce Made Using the Developed Ultra-thin and Flexible LED Lighting Panel Technology

Left: non illuminated state; Right: illuminated state.

Source: Lucent Optics, Inc.

Discussion of the Prototyping and Testing Results

The developed lighting panel prototypes demonstrate that Lucent Optics' CoreGLO technology platform is suitable for make large-area, highly efficient diffuse light sources with thin and flexible forms and using very small amounts of raw materials. The panels were prototyped in sizes that are some of the most popular ones among linear lighting fixtures such as fluorescent troffers and suspended linear fluorescent fixtures, as well as in a custom size. The largest of the developed prototypes (48″x24″) sets a new world record for the size of a thin and flexible lighting panel with diffuse emission, breaking a Lucent Optics' previous record of 24″ x 24″ for this type of light sources and meeting the respective technical goal of this project.

The weight of the lighting panels was reduced to only 0.5 lbs./ft^2 which represents the industry's lowest weight per unit area for any type of diffuse light sources. This is a result the focused effort on lowering the material intensity of the light panel. The largest reduction was achieved due to reducing the thickness of the optical layers (such as the optical waveguide), eliminating optical diffusers, and reducing material redundancies in the panel structure and particularly its support frame. It is estimated that this reduction in the weight and material intensity in the CoreGLO panel and the LED troffer compared to traditional fluorescent and LED fixtures should lower the cost of next-generation linear lighting fixtures by 30 to 50 percent when manufactured in high production volumes.

Despite having thin and flexible forms and using extremely small amounts of raw materials, the developed panels have shown to provide a relatively high light output, outperforming most lighting panels available on the market today. For example, the 48" x 12" panel was demonstrated to output 8,700 to 9,000 lumens, depending on its configuration, while the output of "industry-standard" fluorescent or LED troffers of this size ranges from 3,000 to 4,500 lumens. At the same time, the measured efficacy of the prototype panels approached and, in several configurations, exceeded 120 lm/W, thus, meeting the performance goals set for this project and putting the developed panels in a high-performance category of large-area diffuse light sources. All this makes the developed technology attractive for general lighting applications and particularly for replacing linear lighting fixtures such as 1'x4', 2'x2', and 2'x4' troffers which are extremely popular in commercial buildings.

Prototyping a first-of-a-kind, full-size 2'x4' volumetric LED troffer using a similarly sized CoreGLO panel has demonstrated how the material-saving features of the CoreGLO technology can be translated into the finished lighting fixture, showing a 50 percent reduction of the weight of the fixture comparted to the state of the art. Unlike other volumetric troffers which typically have a relatively narrow and excessively bright central area within a trough-shaped reflector, the developed troffer uniformly emits light from its entire surface. Therefore, despite a much higher lumen output compared to the conventional troffers, the emission of the developed troffer is much softer and better distributed. This, in turn, significantly reduces the glare probability and improves the overall aesthetics of the fixture. The achieved significant reduction of the weight of the lighting panels should also allow for reducing the transportation and installation costs. For example, even at its demonstrated largest size of 2'x4', the developed LED troffer can be easily handled by a single person and installed as a drop-in insert into the ceiling grid.

The tubular wall sconce marks the industry's first high-performance LED lighting fixture with a cylindrically shaped waveguide and the respective unique appearance of a hollow, translucent body which emits light from its surface rather than being backlit by a light source located inside such a body.

The developed lighting fixtures, besides providing lumen output and efficacies matching or exceeding industry standard high-performance linear lighting fixtures, demonstrate unique, visually attractive appearances, featuring a curved shape of the light emitting surface and a decorative geometrical pattern of the emission. The developed fixtures are also fully dimmable and color tunable with a CRI of 90+, which is further consistent with classifying them as a high-performance lighting fixtures which can be considered for replacing conventional linear fluorescent and LED lighting systems. The demonstrated operability of the developed systems with state-of-the-art LED drivers indicates that they can be readily integrated with daylighting controls and other systems in a smart building/smart grid environment.

CHAPTER 9: Technology/Knowledge/Market Transfer Activities

Conference Presentations

Vasylyev S., "Ultra-thin Flexible LED Lighting Panels", Clean Energy Technology Showcase, October 2019, California Energy Commission, Sacramento, CA.

Lucent Optics, Inc. Live demo of ultra-thin flexible LED lighting panel technology. Clean Energy Technology Showcase, October 2019, California Energy Commission, Sacramento, CA.

Vasylyev S., "New Opportunities for Interior Lighting Design Using Flexible Wide-area Light Sources", EPIC Forum (Virtual): Reimagining Buildings for a Carbon Neutral Future, September 2020 California Energy Commission.

Vasylyev S., "Designing Wide-Area LED Luminaires with Ultra-thin and Flexible Form Factors", Panel: Directions in Optical Control, US DOE SSL R&D Workshop, Jan. 2020, San Diego, CA.

Vasylyev S., Masalitin N., "Ultra-Thin Flexible LED Lighting Panel", Poster Presentation/Live Demo, US DOE SSL R&D Workshop, Jan. 2020, San Diego, CA.

Vasylyev S., "Glare Reduction Using Thin-Sheet Optical Waveguides", Panel: "Glare and Diffuse Lighting", US DOE SSL R&D Workshop, Feb. 2021. https://www.energy.gov/eere/ssl/2021-lighting-rd-workshop

Vasylyev S., "Diffuse Thin-sheet Light Sources Using LED-illuminated Waveguides", US DOE SSL R&D Workshop, February 2022. https://www.energy.gov/eere/ssl/2022-solid-state-lighting-workshop

Vasylyev S., Masalitin N., "Ultra-Thin Flexible LED Lighting Panel", Poster Presentation, US DOE SSL R&D Workshop, Jan. 2020, Jan. 31 – Feb. 3, 2022.

Industry Recognitions and Awards

Lucent Optics' CoreGLO LED lighting panels were selected by the Illuminating Engineering Society for inclusion in the 2021 IES Progress Report which recognizes significant new advancements in lighting products, research, publications, and design tools for its annual report. Illuminating Engineering Society, 2021 Progress Report, p. 54.

Technology Commercialization

Initially, Lucent Optics commercialized key components of CoreGLO panels, including microprinted optical waveguides ranging in sizes from 8″x12″ to 24″x24″ as well as low-profile LED strip engines compatible with these waveguides. The continued technology development has led to waveguide offerings in larger sizes and the launch of the Lucent Optics' first integrated illumination product: the CoreGLO LED lighting panel. This panel is available in several standard configurations and as a fully customizable product. It can be configured for one-sided or two-sided emission (such as for direct/indirect lighting) and transparent or translucent appearance at wall-plug efficacies of up to 122 lm/W. Available options also include different color temperatures and color rendering, as well as a selection of decorative emission patterns. Lucent Optics’ customers include manufacturers of electronic displays, illuminated signs, and general lighting products. The optical waveguides and backlighting structures of Lucent Optics’ patented designs can also be found in a variety of mass-produced consumer products employing LED-illuminated displays.

CHAPTER 10:
Benefits to California

Project Innovation

California buildings contain hundreds of millions fluorescent tubes that unnecessarily consume vast amounts of energy, provide suboptimal lighting quality, require frequent replacements, and pose environmental hazards. The replacement of linear fluorescent lights with Solid State Lighting technology, such as LEDs, has the largest energy saving potential among all types of light fixtures (source: DOE). However, LED penetration into this market is still very low. The high cost of LED-based luminaires and the lack of distinct, innovative designs are critical factors that contribute to slowing the adoption of LED technology. New luminaire designs having improved aesthetics and reduced cost and material intensity are needed to overcome the LED adoption barriers and unlock the full energy saving potential of solid-state lighting.

This project has further developed a new technology platform (CoreGLO™) for making a wide range of aesthetically appealing, wide-area LED luminaires of various innovative designs and shapes at a fraction of the cost of traditional fluorescent and solid-state fixtures. The core innovation employed in this project was combining a thin and flexible plastic sheet with edge-coupled LEDs to distribute light with high efficiency and uniformity and to obtain an energy efficient light source with thin and flexible forms. Key advantages of this innovation include supporting new luminaire designs, improved light quality and aesthetics with homogeneous surface emission and no glare from LEDs, extremely low intake of raw materials, low cost, and new ways of lighting integration into buildings.

Ratepayer Benefits

CoreGLO lighting panels are expected to help achieve the state’s energy goals of reducing electricity consumption in buildings by lowering the barriers for a broader adoption of energy-efficient LED technology and expediting the replacement of incumbent fluorescent lights (such as 2’x2’, 1’x4’, and 2’x4’ troffers and suspended fixtures employing T5, T8, and T12 fluorescent tubes). This new type of lighting panels may also help solve common problems associated with linear fixtures, including environmental hazards due to the mercury content in fluorescent lamps, poor quality of light, subpar aesthetics, and the need of periodic lamp replacements. Considering the superior lighting performance and ultra-thin, material efficient design, CoreGLO panels may provide a much more pleasant, distributed, and long-lasting light source that can be seamlessly integrated into building interiors and could help create a more comfortable, ambient indoor lighting environment in all types of commercial buildings (offices, hospitality, warehouses, medical, retail educational), thus benefiting a wide range of ratepayers.

Specific Benefits

- Lower costs: By using extremely small quantities of raw materials and weighing less than 0.5 lbs/ft^2, CoreGLO reduces the manufacturing, shipping and installation costs.

- Greater reliability: The high-efficacy CoreGLO panels will help reduce electricity consumption by buildings, peak demand and electric grid loads, thus contributing to improved grid reliability.
- Economic development: By providing new lighting fixture design opportunities and helping increase the rate of fluorescent fixture replacements with LED sources, CoreGLO would create new business opportunities for lighting manufacturers and installation contractors.
- Environmental benefits: The low intake of raw materials and inherent energy efficiency of CoreGLO luminaires will help improve sustainability of the buildings, reduce their environmental footprint and associated CO2 emissions.
- Public health: The replacement of linear fluorescent fixtures with, LED-based CoreGLO panels will eliminate the risk of breakage and the need of periodic discarding the mercury-containing fluorescent tubes, thus reducing the health hazards related to toxic materials release from such tubes.
- Consumer appeal: The thin and flexible forms of CoreGLO panels create virtually unlimited design opportunities, including light panel integration into various surfaces of building interior and making aesthetically appealing lighting fixtures and systems.
- Energy security: The improvement in energy efficiency in the commercial and residential building sectors due to replacing inefficient fluorescent fixtures with high-efficacy CoreGLO panels will reduce overall demand for energy and thus contribute to the improving energy security.

GLOSSARY AND LIST OF ACROYNMS

Term	Definition
Candela (cd)	A unit of luminous intensity indicating luminous power per unit solid angle emitted by a light source in a particular direction.
CCT	Correlated Color Temperature: a description of color of light relative to the radiative emission of heated black body and reported in temperature units of Kelvin.
CEC	California Energy Commission
CRI	Color Rendering Index: the ability of a light source to reflect the color of illuminated objects with fidelity relative to ideal or natural light sources of the same color temperature.
Embodied Energy	Calculation of all the energy that is used to produce the product.
Efficacy (Luminous)	A measure of light source efficiency in producing visible light LED relatively the electrical power input. The luminous efficacy is calculated by dividing the Lumens (lm) of produced light by Watts (W) of the input power and is generally characterized in terms of lm/W.
LED	Light Emitting Diode: a solid-state semiconductor light source that emits light when current flows through it.
Light Guide	See "Waveguide"
Lumen (lm)	International unit of luminous flux, a measure of the total quantity of visible light emitted by a given light source.
Luminaire	A complete lighting unit or system used for space illumination.
Luminance	A measure of the luminous flux per unit solid angle and unit source area.
Nanometer (nm)	A unit of length equal to one billionth of a meter.
NVLAP	National Voluntary Laboratory Accreditation Program administered by the National Institute of Standards and Technology (NIST).
OLED	Organic Light Emitting Diode (organic LED): an LED which includes an organic light-emitting compound or film.
Solid-state lighting	A type of lighting that uses semiconductor devices or materials as light sources rather than electrical filaments or ionized gas, for example.
TWh	Terawatt hours
TBtu	One trillion British thermal units

Term	Definition
Troffer	A common type of lighting fixture, usually of a rectangular shape (i.e. 2' by 2', 1’ by 4’, or 2' by 4'), that fits into a modular dropped ceiling grid or is mounted to the ceiling surface.
Watt (W)	A unit of electrical power equal to one ampere under the voltage of one volt.
Waveguide	An optical structure that can guide light along its body.

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