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Lighting R&D Program: Luminaire Integration and Market Expectations R&D Meeting

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DOE Lighting R&D Program, "Luminaire Integration and Market Expectations R&D Meeting", February 2021

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Comments

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1 Introduction

On October 28, 2020, experts in organic and quantum dot light emitting devices gathered at the invitation of the Department of Energy (DOE) Lighting R&D Program to help identify critical research and development (R&D) topic areas in the fields of luminaire integration and meeting customer expectations. This year, for the first time, the meeting was held virtually due to travel difficulties and concerns related to the ongoing COVID-19 pandemic. The meeting commenced with "soapbox" presentations where each participant was invited to give a short presentation describing the state of understanding of the integration of organic light-emitting diode (OLED) luminaires that meet market demands, to identify gaps and suggest new R&D to advance understanding. The presentations were followed by a general discussion of the R&D challenges and barriers to implementation. Finally, the participants were asked to contribute ideas regarding program content for the upcoming R&D Workshop to be held February 1-4, 2021.

The meeting format provided an opportunity for OLED and materials experts in the field to exchange ideas and explore collaborative research concepts. Participants included invited experts in science and engineering drawn from academia and industry.

This report summarizes the outcome of the discussions on critical technology challenges and identifies corresponding R&D tasks within the existing task structure. Outlines of the participants' soapbox presentations and related remarks are included in Appendix A: Participant Presentations of the report.

1.1 Key Conclusions

The meeting format encouraged each of the attendees to participate and present their perspectives on critical R&D challenges. The discussions ranged from device design and material selection to manufacturing techniques, with overall goals of reducing cost and enhancing performance. The major conclusions can be divided into three areas, as described in more detail in Section 2:

- Panel Structures and Performance: Cost reduction and improved efficacy remain as the most urgent requirements, especially for conformable panels. Better spectral control and increased light production will enable new applications.
- Drivers and Power Supplies: The development of multi-channel drivers and reductions in cost and size remain as top goals.
- Market Expectations: Recent technical improvements have addressed most of the deficiencies in previous products and new application areas are opening up. Further market education is needed to inform the lighting community of updates in OLED performance and to explain the benefits of new forms of diffuse lighting.
- Alternative Approaches: Quantum dots and perovskites offer alternative sources for light production in diffuse light sources. They could be incorporated into similar luminaire structures as those for OLEDs, but currently do not offer better advantage in performance. The development of mini-LEDs could lead to substantial reductions in the thickness and weight of edge-lit LEDs. Further exploration of hybrid systems could be fruitful.

2 Critical R&D Topic Areas

2.1 Panel Structures and Performance

The discussion covered both OLED panels and edge-lit LED waveguides. Broad adoption is key to achieving the significant energy savings promised by solid-state lighting (SSL) technology. Diffuse light sources need to reduce costs while continuing to improve performance. Developments must be guided by market opportunities for luminaires that cannot be met by fixtures based on compact light sources.

2.1.1 Physical Dimensions

The dominant luminaire that provides a diffuse light source is the troffer. These can be made more efficient by replacing the fluorescent tubes with linear strips of LEDs within the same thick, heavy luminaire. A typical 2' x 2' fixture provides between 3000 and 7000 lm, which corresponds to 4,000 to 9,000 lm/m^2, with efficacy in the range from 100 lm/W to 130 lm/W. The thickness and weight can be reduced by using flat panel lights, with a waveguide lit by LEDs on one or more edges. The thickness of the waveguide is typically in the range of 5 mm to 15 mm, but the addition of frames or drivers can bring this up to 50 mm. Weight varies from around 2 kg for a 2' x 2' panel (~6 kg/m^2) up to 10kg for a 2' x 4' fixture (~15 kg/m^2). Efficacy is also usually in the range of 100 lm/W to 130 lm/W.

OLED thickness for rigid panels is currently between 1.4 mm and 2.1 mm, but this does not include the driver. The weight is 38-70 g for a panel with lit area of 100 mm x 100 mm, which corresponds to 3.8-7 kg/m^2. For flexible OLEDs the thickness is currently between 0.6 mm, and the weight is 15 g for a panel with lit area of 221 mm x 46 mm, which corresponds to 1.5 kg/m^2.

The major challenge is to develop a strategy for scaling to larger light production. In the past this has been met by including many non-contiguous panels in a single luminaire. Interest was expressed in the possibility of freeing one or two borders to create longer luminaires (for example in pendants). The automobile industry has expressed a demand for segmented panels, with control of the intensity in each segment. These could perhaps stretch across the whole rear of the vehicle. Extremely large sheets that might be deployed as OLED wallpaper is seen as unviable and without many proponents. One of the issues that must be resolved as the total amount of light is increased is the avoidance of glare. OLEDs have often been promoted as providing soft lighting, but the exact meaning of that term needs to be clarified.

2.1.2 Efficacy and Lifetime

The two most important short-term goals on efficacy are to raise the value for white light to over 120 lm/W, thereby exceeding the current performance of most diffuse LED luminaires, and to remove the penalty for flexibility. Through support by the DOE Lighting R&D SBIR program, Pixelligent has developed an internal light extraction technology (ILE) that is bendable. That same project has achieved an efficacy of 125 lm/W in a prototype panel with an extraction efficiency of around 50%. If stable phosphorescent or hyperfluorescent blue emitters become available and extraction efficiency can be raised to the DOE target of 70%, the luminaire efficacy could reach over 150 lm/W within the next five years and meet the long-term target of 180lm/W before 2035.

The lifetime of OLED panels seems to be adequate for most current applications, but R&D on stability and reliability is still needed, particularly at high current densities. For example, reduction in the number of stacks from 6 to 3 would lead to substantially lower cost for organic materials and capital expenditures in deposition equipment. Success in automobile applications could be extended if the brightness could be increased to that needed for brake lights without any penalty in lifetime.

2.1.3 Spectrum

The major recent advances in spectral control for general lighting applications have come from narrowing of the red peak to cut down emission in the infrared region. With respect to the need for a better blue emitter, the stability is very sensitive to the photon energy and thus the wavelength. It is possible that a light blue emitter that meets the need for lighting applications could become available before the deep blue emitter preferred in display applications. Avoiding very low wavelengths also helps to reduce blue light hazards. Determination of the best peak wavelength for general lighting applications would be helpful for near term progress. The availability of more options for spectral shapes will also drive the adoption of OLEDs in specific applications, such as agriculture, health care and automobiles.

Two approaches to color tuning have been explored in the past. OLEDWorks has proposed a third option. They have developed a dim-to-warm device in which the color temperature is reduced significantly as the intensity is reduced. They suggest that this effect could be combined with pulse-width modulation (PWM) to create color-tunable panels. PWM has been used for dimming in LED lights, but can lead to unintended consequences. In particular, the effect of PWM on flicker and lifetime should be studied.

2.2 Drivers and Power Supplies

One of the critical tasks in converting an OLED panel into a luminaire is the control of the supply of electrical current. This begins with the connections on the edges of the panel. For homogeneous panels, these must assure uniformity across the panel, but segmented panels may require more complex connectors. An alternative to the expensive printed circuit boards that are currently used would be welcome.

The development of highly efficient, inexpensive multi-channel drivers represents the most critical R&D challenge. Although the performance of LED drivers has improved significantly and the cost has been reduced, these drivers are not well matched to OLED panels, primarily because of the low power levels. This situation may change as more attention is paid by the LED community to the efficiency of drivers at low dimming levels. In the meantime, custom designed drivers that are used to control single OLED panels are expensive and have relatively large losses, in the range of 10-25%. The driver cost is a substantial fraction of that of the panel and needs to be reduced to around $1 per panel, or below. It is generally believed that this can be achieved most easily through the use of multi-channel drivers to control several panels. This approach may also help to reduce the impact of parasitic losses in power conversion.

In past projects to develop multi-channel displays, one major goal was to compensate for differential aging of panels within a luminaire. This is less of an issue now, because of the longer lifetimes of OLED panels. The goal for lighting is now to enable independent control of the intensity and spectrum of each part of a segmented panel or each panel in a luminaire.

The exploration of the benefits of replacing Si-based components with wide-bandgap semiconductors has begun with a recent DOE Lighting R&D project. The results are very promising, although the cost will initially be higher. Leverage of similar developments in LED drivers could be key to the success of this trend.

Reduction in the size of drivers remains a goal. One possibility is to create slender cylindrical drivers that can be wrapped around a wire. Another, longer-term approach would be to develop thin-film drivers that can be incorporated in the panel.

2.3 Market Expectations

It is generally agreed that a great deal of interest was created in the potential benefits of OLED lighting before the technology was ready to deliver those benefits. Disappointment in the performance of early products led to the withdrawal of major manufacturers in Japan and Korea. Re-education of those customers is now a major challenge. More focused and more realistic marketing strategies are now needed, along with a better assessment of the benefits of OLEDs in different applications.

The most promising short-term application is in automobile applications and exciting new developments have been reported in recent months. Technical progress in this area will be transferable and expanded adoption beyond the high-end market will help to build production volume and reduce costs for all applications.

Another emerging application area is in the educational market, particularly through sales of desk lamps in China, where there is a greater concern about the influence of lighting on the health of students. There are related opportunities to expand the range of OLED products for use in health care facilities, going beyond the provision of amber lights as markers and night-lights.

2.4 Alternative Approaches

While OLEDs have been the most promising source for flexible diffuse lighting panels, other possibilities are emerging. Electroluminescent quantum dots and perovskites could build on much of the infrastructure that has been developed for OLEDs and possibly offer the opportunity for simpler manufacturing. However, their performance is still inferior to that of OLEDs, both in efficacy and lifetime.

Although inorganic LEDs have been used as the light source in rigid liquid crystal displays (LCDs) for many years, the production of flexible flat panel displays has relied almost entirely on OLEDs. The availability of efficient and reliable micro-LEDs may change this situation. The R&D that is now underway on the incorporation of mini-LEDs and micro-LEDs in display backlights may provide opportunities in lighting also. Further development of hybrid luminaires combining the best features of inorganic and organic LEDs should be explored.

Appendix A: Participant Presentations

Michael Boroson, OLEDWorks: Luminaire Integration

Michael Boroson began by pointing out that past R&D has been focused upon substrates, electrodes, organics, encapsulation and light extraction. Other components add significant cost (~33%). A metal foil is added for heat spreading and encapsulation protection. A printed circuit board surrounds the panel for uniformity and electrical connection to drivers and the power supply. Contacts can be made on all four sides. Bendable panels need to be mounted on a rigid support to maintain curvature and to protect from glass breakage. This is accomplished using a double-sided adhesive with high thermal conductivity.

Individual drivers are currently attached to each panel, at an unacceptably high cost. There is an urgent need for low multi-channel drivers that can control several panels or multiple segments in a single panel. These drivers should be compatible with automated controls and sensors. Following the discovery that OLED stacks can be designed to emit light at lower color temperatures as the brightness is reduced, pulse-width modulation could be introduced to produce color-tunable devices. Reduction in driver size, as well as cost, will help drive greater adoption of OLED lighting.

Joe Miller, LED Specialists: OLED Integration and Manufacturing Challenges

The development of multi-panel drivers is essential for the commercial success of OLED luminaires. Drivers for inorganic LEDs are well established with many competing suppliers and established standards. Performance and cost are mature and LED drivers are becoming commodities. However, they are not suitable for OLEDs. OLED panels are low power devices that can be connected more simply to building power supplies. The development of custom drivers has led to high costs. There are few suppliers and no standards. Improvements in driver efficiency and cost reduction will contribute significantly to lowering the total cost of ownership of OLED fixtures.

LED specialists is exploring the use of wide bandgap semiconductors in drivers which could be smaller, faster, more reliable, and more efficient than their silicon (Si)-based counterparts. Their goals are to eliminate up to 90% of the power losses that currently occur during AC-to-DC and DC-to-AC electricity conversion and to enable higher-temperature operation. These goals have been met and further aspects of driver performance are being addressed, such as the power factor and total harmonic distortion.

Dan Schwade, Acuity Brands

Early OLED luminaires attracted a lot of attention but did not provide practical light levels and were not robust at the components level. Some critical luminaire manufacturers experienced substantial disappointment in the performance of panels from foreign suppliers who have now left the market. Further market education is required to demonstrate that these past issues have been addressed, and to explain the befits of cool operation, broadband spectra and uniformity of illumination.

Short-term needs include:

- Proven integration techniques for flexible panels so that lighting manufacturers can be comfortable offering this technology
- Additional color options with lower costs and simple color tuning
- More driver options with higher system efficacy, lower costs and easier luminaire integration
- Translation of the progress made with segmented panels in automobile applications to general lighting - demonstrate and develop solutions for wayfinding, signalling and interactive response (occupancy, safety, etc.)

Some longer-term needs are:

- Borderless options - remove one or more unlit edges to create continuously lit forms, enabling the original vision of large uninterrupted sheets of light
- Additional sizes and shapes to facilitate more luminaire form factors
- Spectral tuning solutions to match circadian rhythms, plant growth, and targeted color enhancement
- Segmented panels with practical control solutions and advanced drivers
- Compatibility with DC to DC micro power grids, the Well Buildings standards, LEED and new building power systems

Sergey Vasylyev, Lucent Optics: New Opportunities for SSL Using Sheet-Form LED Sources

Lucent Optics is developing planar light sources that are lit by LEDs but go beyond legacy form factors. By leveraging manufacturing advances, they aim to improve material efficiency, cost and sustainability. Their CoreGLO™ platform distributes the light from off-the-shelf LEDs along two edges through micro-patterned flexible plastic waveguides. Efficacy of over 100 lm/W is achieved in panels of 1 mm thickness and weight of 0.5 lb/ft^2. Approximately 92% of the light from the LEDs is injected into the waveguide and ~85% emerges into air, with spatial uniformity of over 90%. The surface of the waveguide can appear to be homogeneous or patterned.

In response to questions, Vasylyev stated that the greatest demand is for sizes up to 2 x 4 ft. Although the availability of mini- and micro-LEDs will allow the thickness of the waveguide to be as low as 100 µm, customers rarely ask about thickness. Flexibility requires thickness below 2 mm.

Larry Sadwick, Innosys: OLEDs and LEDs – Diffusion, Efficacy, Glare, Efficiency, Flexibility and Thinness along with the 3 Ps

It needs to be remembered that very few customers value performance over price. The typical retail cost for 2' x 2' flat panel lights is $40 to $50, or ~$120/m^2. Innosys currently supplies color-tunable flat panels with width of 4.5 mm and efficacy of ~130 lm/W lit by inorganic LEDs. They are able to offer drivers with total losses of only 5%, but most customers prefer to save money by using less efficient drivers. Power factors over 98% and total harmonic distortion less than 10% are achievable.

The emphasis on price means that almost all SSL replacements for fluorescent lights are made in China. Larry believes that DOE support for U.S. manufacturing of SSL should be given high priority and could enable the domestic production of flexible, ultra-efficient, low-mass luminaires that meet customer price-points.

Kathy Vaeth, OLEDWorks: The OLED Lighting Experience

OLEDWorks is involved in general lighting, custom markets (for both white and color panels), micro-displays, and embedded lighting (automotive, rail, appliance, medical, furniture, etc.). The characteristics that customers appreciate are (in order)

- Uniform surface illumination
- Thin planar light source
- High quality segmentation
- Naturally diffuse
- Low glare
- Excellent color rendering
- Efficient and controllable

OLEDWorks offers bright panels with excellent color (CRI > 90; R9 > 50) at correlated color temperature (CCT) of 3000K or 4000K with lifetimes over 30,000 hours and efficacy over 60 lm/W at the highest brightness. This level of performance already provides competitive advantage in some applications, such as automobile rear lights and machine vision.

Automotive applications will drive volume and reliability capabilities. The resulting innovations will be leveraged in general lighting. The 2020 application of OLED taillights features the activation of 6 OLED light segments per panel. The next generation of OLED taillights will feature over 50 OLED light segments that can be activated as needed, with their brightness continuously adjusted. This allows for further innovation through precise display signals, symbols, and even messages.

Vaeth noted the following trends in market development:

- Human Centric Lighting for eye health, color response, hygiene; more studies are needed on this topic
- Automated controls, DC wired in buildings, new drivers and integration strategies
- Agriculture: indoor and vertical farms
- There is enthusiasm for curved form factors, but cost is currently a barrier
- Segmentation and logos present exciting new design opportunities
- Special applications such as machine vision and wayfinding

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