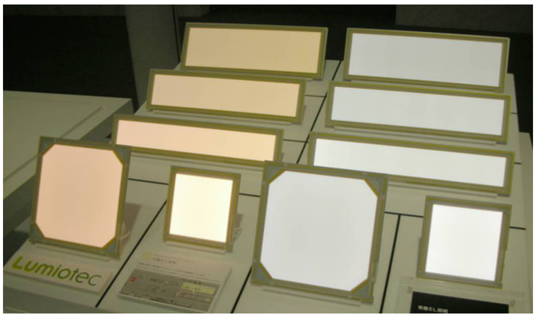
Development and Mass-Production of an OLED Lighting Panel - Most-Promising Next-Generation Lighting -



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Lumiotec Inc. is the only company in the world that specializes in the mass-production and distribution of organic light-emitting diode (OLED) lighting panels, the most-promising next-generation lighting source. The company started manufacturing and selling a total of 10 models in January 2011. They are available in five shapes (square in two sizes, large and small; and rectangle in three sizes, large, medium, and small), with each model in two lighting colors (warm white and natural white). In September 2011, the company also started selling two types of design luminaires (product names: HANGER and VANITY), incorporating, for the first time in the world, a mass-produced OLED lighting panel and a dedicated compact driver module. In the development of the next-generation panels, the company used phosphorescent materials to achieve a luminous efficacy of 40 lm/W, and developed new panels with high efficiency, high luminance, and long lifetime.

1. Introduction

To study the feasibility of OLED lighting panels, Lumiotec was established in May 2008 as the world's first company specializing in lighting OLED panels. Investment was provided from companies such as Mitsubishi Heavy Industries, Ltd. (MHI), Rohm Co., Ltd., Toppan Printing Co., Ltd. and Mitsui & Co., Ltd.

Unlike existing light sources, such as incandescent light bulbs and fluorescent lamps, OLEDs are planar light emitters that are lightweight and have thin profiles. This allows lamp manufacturers and designers to create unprecedented designs and provide dramatic effects, leading to the creation of new living environments in houses, offices, stores, and vehicles such as cars and airplanes. OLEDs can provide safe and comfortable lighting for general consumers because, unlike fluorescent lamps, they do not contain mercury or other harmful substances. They emit UV-free soft light that is gentle on the skin and eyes and has a high color-rendering index.

Based on multi-photon emission device (MPE) technology and in-line deposition technology with linear evaporation sources, we constructed a mass-production line in Yonezawa City in Yamagata Prefecture, Japan, for the development and production of OLED lighting panels. The former technology is a method to achieve both high luminance and long lifetimes. Typically these parameters are considered to be in a trade-off relationship. The latter technology is a technique to significantly increase the efficiency of material use and reduce the time required for multi-layered film formation.

2. Development of High-luminance and Long-lifetime Panels

2.1 OLED devices for lighting applications

An OLED device is a planar light-emitting diode using an organic semiconductor. Taking advantage of its characteristics, OLED devices were first employed in displays. In recent years, high expectations have been placed on these devices as next-generation lighting sources, along with

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LED lamps. Because light sources for lamps require luminance more than 10 times that of displays, achieving both high-luminance and long-lifetime has always been a major challenge. Lumiotec succeeded in achieving high-luminance uniform light emission over a large panel via the MPE technology. In this method, multiple layers of emission units are laminated so that the current efficiency (luminance) is multiplied almost by the number of emission units. An MPE device (the structure and principle of which are shown in **Figure 1**) uses a technology to laminate emission units in series with a charge generation layer interposed inbetween[**1]. This makes it possible to simultaneously achieve high-luminance and long-lifetimes.

**1: Joint patent owners are MHI, Rohm, and Professor Kido of Yamagata University. Lumiotec is the only licensee.

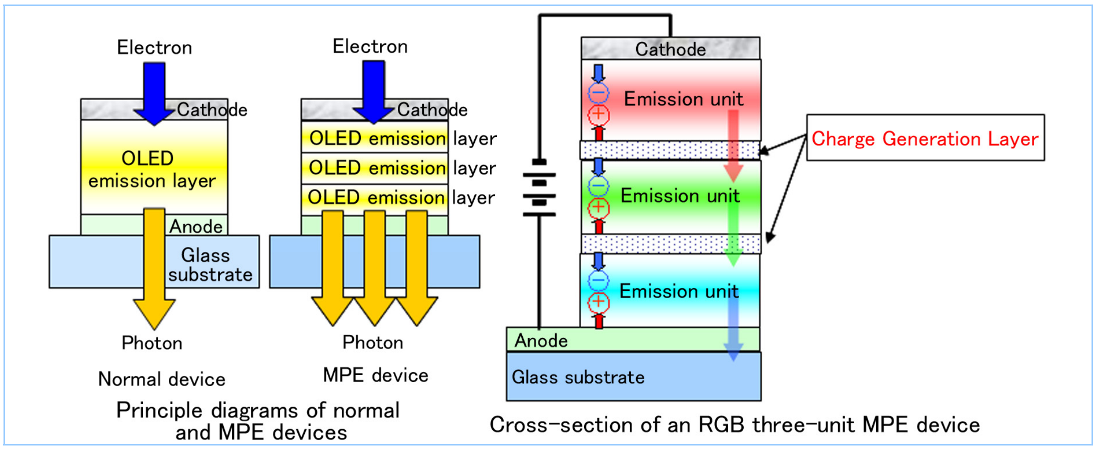


Figure 1 Principle and cross-sectional diagrams of multi-photon emission devices

2.2 Performance required for lighting OLED panels

In addition to their high-luminance and long-lifetime, OLED lighting panels are required to have high luminous efficacy (units: lm/W) and a high color-rendering index (index of color reproducibility). They should also be compliant with the standards of lighting colors (color temperature and chromaticity coordinates). Angular dependence on emission, changes after aging, and variation among individual devices should also be within a certain range[**2]. We are trying to develop a practical product, while keeping in mind that we need to achieve all of these features in a well-balanced way.

**2: Standards for solid-state lighting colors are mainly intended for LED lamps. Further discussion is required at international standardization conferences.

2.3 Development and production of high-luminance and long-lifetime devices

White OLED lighting devices are designed to achieve a white color by simultaneously emitting light from organic substances that radiate in colors such as blue, red, and green. However, changes in lighting colors due to aging (color shift) are inevitable because the durability of devices differs from color to color. This is an issue that must be addressed in addition to the issue of luminance lifetime. (A comparison of OLED device structures is shown in **Figure 2**.)

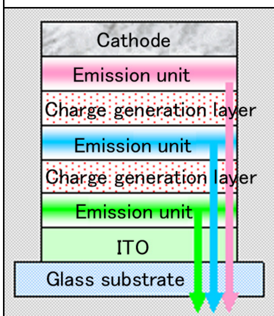
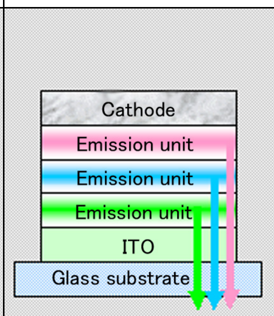
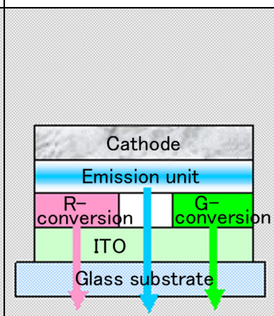
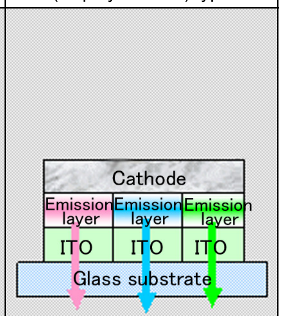
Multi-unit (MPE) type	Multi-layer emission type	Color conversion type	Superposition (display method) type
			
In the case of “n” laminated units, the luminance is increased nearly n-fold; at a fixed luminance, the current is reduced to 1/n.	Capable of mixing colors with a simple structure but has problems delivering high luminance.	Color shift after aging is less significant but requires a costly color conversion layer and has problems delivering high luminance.	Capable of adjusting colors as with displays, but requires a complicated and expensive drive circuit and has problems delivering high luminance.

Figure 2 Comparison of light-emitting device structures

To cope with the color shift, we have tried to lengthen the lifetime of the blue devices, which have the lowest durability. We discovered that the most essential factor is to maintain carrier balance of electrons and holes over a long period of time. We succeeded in developing a stable carrier transport structure that produced a blue device with a lifetime more than five times longer than that of existing blue devices. This dramatically increased the color shift lifetime, and led us to launch a panel product that performed at practical levels. (The specifications of the panel products are shown in **Table 1**.)

Table 1 Performances of a standard panel

Item	Units	Type of color	
		Warm white	Natural white
Panel outer dimensions	(W × L × t) mm	145 × 145 × 2.3	
Panel weight	g	107	
Dimensions of emission area	mm	125 × 125 (150 cm^2)	
Total luminous flux	lm	99	99
Rated current	A	0.9	0.9
Rated voltage	V	10.7	10.5
Luminous efficacy	lm/W	10.3	10.5
Color temperature	K	2,800	4,900
General color rendering index	Ra	82	81
Chromaticity coordinates	(x, y)	(0.45, 0.42)	(0.35, 0.38)
Rated luminance	cd/m^2	2,800	2,700
Half-decay luminance lifetime	h (1,000cd/m^2)	50,000	100,000
	h (3,000cd/m^2)	10,000	20,000

3. Development of Light Out-Coupling Technology

In an OLED device structure, multiple organic layers are vacuum-deposited on a glass substrate on which a transparent electrode (ITO**3) film is formed, and a metal layer is deposited as a cathode. The outgoing light from the emission layer of the organic layers propagates in all directions, and is emitted to outside from the glass substrate along with light reflected on the cathode. However, the light that is totally reflected on the boundaries between the glass and ITO and between the glass and external air layer is not emitted. Instead it remains inside and attenuates due to differences in the refractive index. Thus, the actual amount of out-coupled light is only about 20% of the total light emission. To effectively extract light in the substrate mode, Lumiotec jointly developed a light out-coupling film (a resin film with a prism lens formed on the surface) with its parent company, Toppan Printing. The film was attached on the surface of the glass substrate to reduce the reflectance on the boundary between the glass and external air layer, thereby improving the light out-coupling efficiency (up to 1.5 times). (**Figure 3** shows the light propagation mode of OLED devices and the effects of the light out-coupling film.)

**3: Abbreviation for indium tin oxide.

The light out-coupling film was obtained by integrating optical design technology owned by Toppan Printing with other microfabrication techniques. We plan to further improve the light out-coupling efficiency in tandem with the optical design of OLED devices, and collaborate in the development of a new light out-coupling structure technology targeting the loss reduction of the thin-film mode.

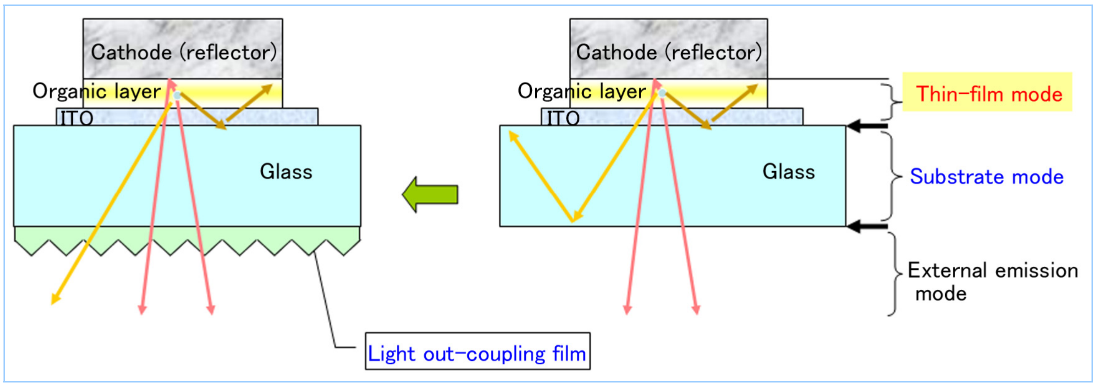


Figure 3 Light propagation mode of OLED devices and effects of the light out-coupling film

4. Development of Encapsulation Technology

4.1 Encapsulation technology for OLED lighting

To prevent degradation of OLED devices, the substrate on which the devices are formed needs to be encapsulated with a glass cap or other means. In OLED displays, devices are normally encapsulated by filling gas such as nitrogen, but this type of encapsulation suffers from poor heat conductivity and thus cannot withstand high-power input for lighting applications. If turned on at a high luminance, the device would be overheated due to insufficient heat dissipation around the power-feeding terminal and, at worst, damaged by thermal runaway. Thus far, fluorine-based or other types of insulating oil have been used for encapsulation to improve the heat dissipation to a certain degree, but the method is less productive and has limitations.

4.2 New encapsulation technology

While addressing these problems, we also strived to provide encapsulation using a common less-costly plate glass substrate, instead of an expensive cavity cap, and developed a gel encapsulation process. Gel is a material that has properties between solid and liquid. It is easier to handle than liquid. In addition, gel-based encapsulation does not require stringent considerations for impacts on the OLED device or an expensive vacuum process, unlike solid encapsulation. We have developed a mass-production process that uses techniques such as dispensing, printing, and bonding, which are commonly used in manufacturing processes of flat panel displays.

We selected a gel material that does not cause device deterioration, and dispersed an inorganic desiccant in the gel instead of using desiccant attached to a cap. Consequently, the heat conductivity and heat dissipation were both improved. In addition, we achieved an encapsulation performance comparable to that of the existing process, while at the same time reducing the panel thickness to 2.3mm.

As a result, when comparing 142-mm square panels at 5,000 cd/m^2, the panel temperature was reduced by approximately 12^{o}C at maximum (**Figure 4**). This improved the lifetime and reliability of the panel, making it possible to provide practical OLED lighting panels.

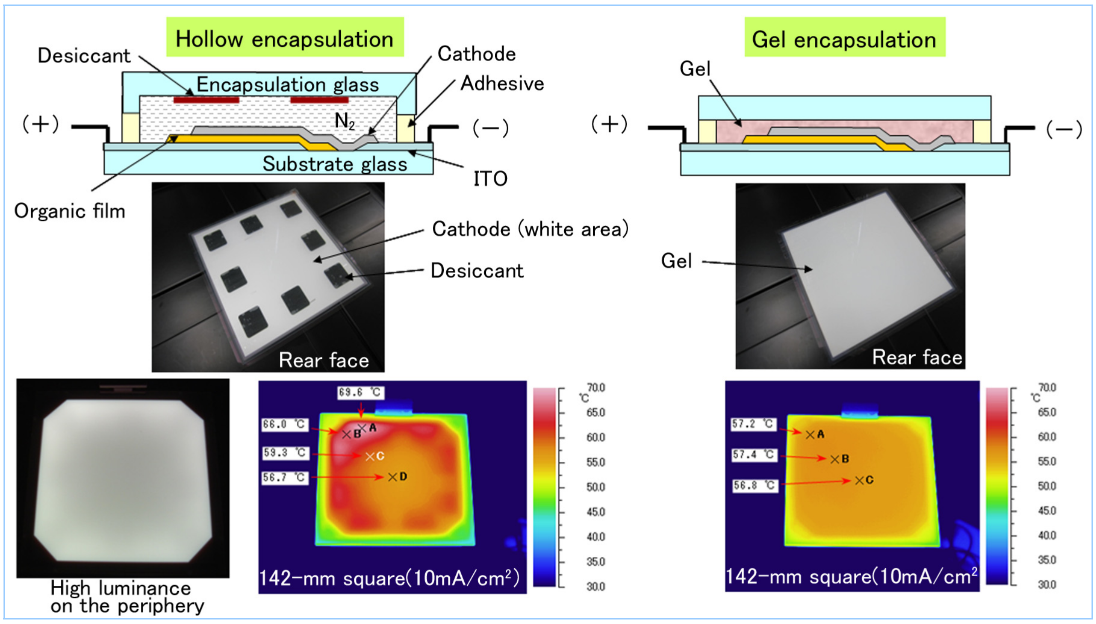


Figure 4 Emission state of panel and heat generation (when lighting at 5,000 cd/m^2)

5. Development of Mass-Production Technology

5.1 Overview of the in-line deposition system

For the film formation equipment, which is the most crucial aspect in the manufacturing process, we use an in-line deposition system with linear evaporation sources developed by MHI (Industrial Machinery Business, Technology & Solutions Division) exclusively for manufacturing for OLED lighting panels. (An overview of this system is shown in **Figure 5**.) The system consists of a vacuum chamber, linear evaporation sources, a substrate carrier, and a vacuum pumping system. The linear evaporation sources are long-length crucibles that evaporate organic materials into a linear form. They are arranged in the vacuum chamber at predetermined intervals according to the number of organic film layers. By continuously conveying glass substrates placed on trays above the linear evaporation sources with only a small gap between the adjacent trays, organic materials are laminated to form a lamination film on the lower side of each substrate (**Figure 6**). The process is suitable for low-cost mass-production of OLED lighting panels because it features a highly efficient use of expensive organic materials and a shorter tact time enabled by continuous conveyance.

Figure 5 Overview of the in-line deposition system

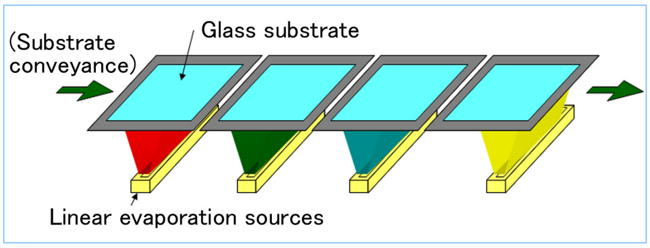


Figure 6 Schematic diagram of linear evaporation sources and in-line conveyance

5.2 Operation results

The in-line deposition system was installed in Lumiotec's Yonezawa Plant in August 2009. Thus far, the system has been operated at full capacity for production and development for more than two years. The system has achieved an in-plane film thickness distribution within ±2% (**Figure 7**), and a long-term deposition rate stability within ±2% for 144-hour continuous operation (**Figure 8**). The in-plane film thickness distribution is an essential factor for producing high-quality panels, while the long-term deposition rate stability is necessary to improve the yield. The system is contributing to the production of panels with stable quality.

Using the system, the company started manufacturing and selling a total of 10 models in January 2011. They are available in five shapes (square in two sizes, large and small; and rectangle in three sizes, large, medium, and small), each model in two lighting colors (warm white and natural white). (See the photo at the top of the article.) Different panel shapes are provided by changing the deposition masks, and various lighting colors of the panels are produced merely by changing some of the light-emitting materials. In this way, production of multiple models can be efficiently realized with only a single deposition system.

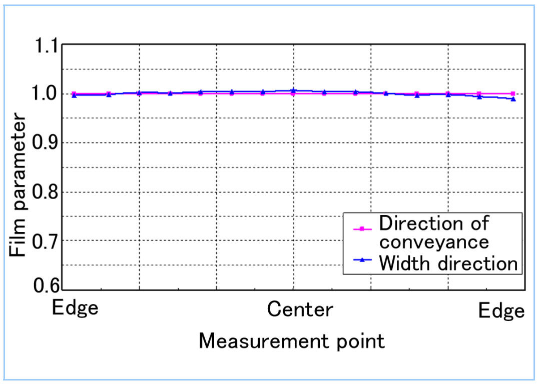


Figure 7 In-plane film thickness distribution

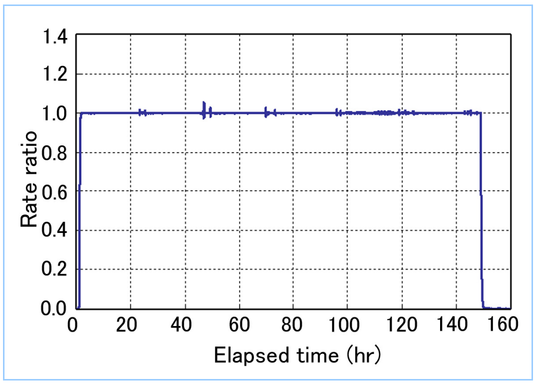


Figure 8 Long-term stability of film deposition rate

6. Development of a Next-Generation Panel

6.1 Latest development status (goals and results)

All the panels launched at the end of fiscal year 2010 used fluorescent materials. However, phosphorescent materials will be used in our next-generation panels, which are slated for launch in spring 2012. The use of phosphorescent materials provided by Universal Display Corporation is an essential technique for improving efficiency, because theoretically they can enhance the internal luminous efficiency by up to 100% (four times as high as that of fluorescent materials). In general, approximately 80% of the light generated in a device is lost in the panel. Thus, “light out-coupling technology” to extract the light otherwise lost will be a key point for development in the future.

With the synergistic effect of these new technologies, our new device achieved a luminous efficacy of 40 lm/W and demonstrated the ability to deliver high-efficiency, high-luminance, and a long-lifetime simultaneously. (The performance specifications of the new OLED lighting panels are shown in **Table 2**.)

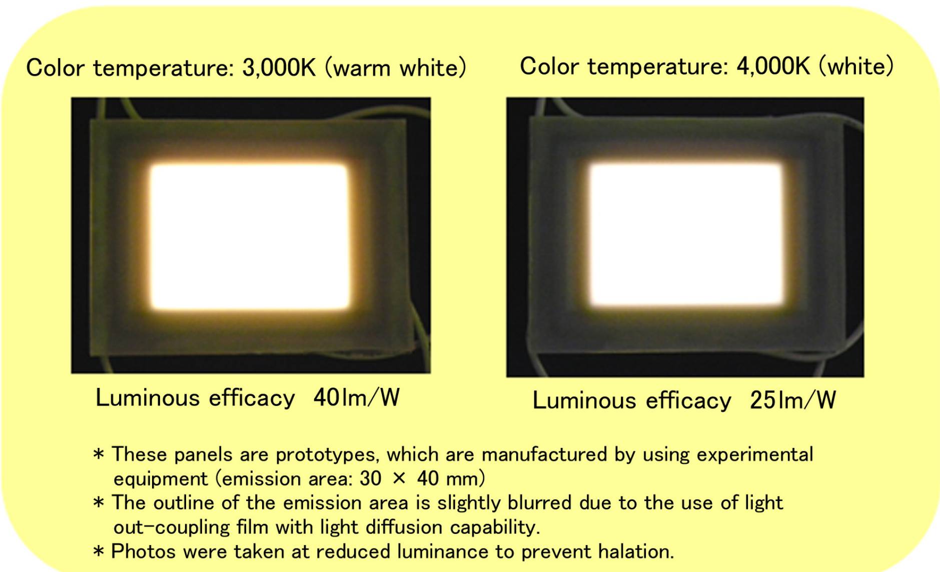
Table 2 Target performances of next-generation panels

Item	Units	Type of color temperature	
		Warm white	White
Panel outer dimensions	(W × L × t)mm	145 × 145 × 2.3	
Panel weight	g	107	
Dimensions of emission area	mm	125 × 125 (156 cm^2) without square electrode	
Total luminous flux	lm	110	110
Rated current	A	0.36	0.49
Rated voltage	V	7.5	9.0
Luminous efficacy	lm/W	40.0	25.0
Color temperature	K	3,000	4,000
General color rendering index	Ra	79	83
Chromaticity coordinates	(x, y)	(0.43, 0.42)	(0.38, 0.38)
Rated luminance	cd/m^2	3,000	3,000
Half-decay luminance lifetime	h (1,000cd/m^2)	60,000	125,000
	h (3,000cd/m^2)	12,000	25,000

6.2 Structure and features of the devices

The new panels incorporate a high-efficiency white MPE device featuring a light out-coupling efficiency that has been significantly improved by our proprietary internal optical path design technique. As a result, the product achieved performances that meet market efficiency requirements. The improved efficiency also has a variety of secondary effects, such as reduced heat generated in the lighting panel (36^{o}C at room temperature), and reduced component costs. We have already developed a high-color temperature model (4,000 K/white) with an efficiency of 25 lm/W, but we plan to aim for higher efficiency in fiscal year 2012.

In the development of new panels, we focused on the issues that have arisen in relation to the existing panels, such as improved luminous efficacy and reduced angular dependence of colors. Because we cannot expect sufficient effects simply by improving the internal luminous efficiency with the use of a phosphorescent emission mechanism, the device structure was entirely revamped to facilitate stable mass-production, low-voltage drive, and out-coupling of light. Furthermore, we adopted a technique for optimizing the optical design to obtain the maximum out-coupling efficiency and uniform angular distribution of wavelengths during the out-coupling film attachment process. With the combined effects of new technologies, we achieved the highest luminous efficacy and longest lifetime for the existing materials, as well as an excellent angular distribution of luminous intensity (**Figure 9**: photo of 30 × 40-mm prototype panels).



The panels incorporate UniversalPHOLED® phosphorescent OLED technology and materials from Universal Display Corporation.

Figure 9 Light emission of new panels

7. Conclusion

We started selling two types of design luminaires with our OLED lighting panels in September 2011 (**Figure 10**: portable "HANGER" and desktop "VANITY"). The products were exhibited and well received at one of the largest international furniture trade fairs in the world (Milano Salone) held in Milan, Italy, in March 2011. These are the world's first commercially available luminaires to incorporate a mass-produced OLED lighting panel and a dedicated compact driver module. By developing high-efficiency panels using phosphorescent materials, we will strive to improve further various performance characteristics such as luminous efficacy and to reduce production costs. Through these efforts, we will try to promote the widespread use and commercialization of OLED lighting panels, so that we can make contributions to improving the global environment.

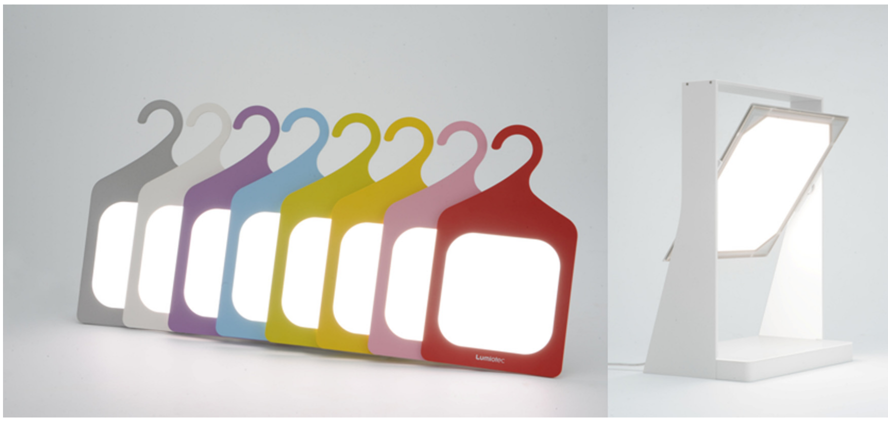


Figure 10 Lumiotec's design luminaires "Hanger" in eight colors and "Vanity"

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