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Abstract. For organic light-emitting-diode (OLED) lighting to be successful, it is critical that it be properly positioned in the marketplace. It is also critical that both the performance and cost be competitive against other lighting technologies in the selected marketplace. This presentation gives an overview of OLED lighting technology from these perspectives. It shows that OLED lighting products should be positioned as luminaires and not light bulbs, which affects both the performance and price expectations. Laboratory OLED devices already demonstrated efficacies that are more than competitive against luminaires based on other lighting technologies. There is potential for substantial further improvement in efficacy. The greatest opportunities come from light-extraction efficiency improvements and from an improved blue emitting system. There has been great recent progress in the OLED device lifetime. To be acceptable as luminaires, however, OLED may need even more lifetime improvements. Not all the improvements need to come from OLED technology improvement, however. We discuss other means to effectively improve the lifetime of OLED lighting panels and show why there is optimism that, with volume production, OLED lighting can be competitive against other luminaires even on the first-cost basis. © *2011 Society of Photo-Optical Instrumentation Engineers (SPIE)*. [DOI: 10.1117/1.3529412]

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1 Introduction

Organic light-emitting-diode (OLED) lighting has been gaining increasing interest in recent years. Many are attracted by certain unique attributes of OLEDs. For example, an OLED is a coated semiconductive device; all the coatings add up to only a fraction of a micron in thickness. Hence, an OLED lighting panel can potentially be made very thin, with its thickness determined only by the substrate and the cover/protective element. An OLED can also be made flexible, stretchable, or even transparent. It can therefore be used in ways never possible before. Like its inorganic light-emitting-diode (LED) cousin, an OLED can be turned on and off instantly, dimmed, and be made to give lights of different color temperatures or even lights of different colors. Although all these features are attractive and can potentially create unique markets for OLED lighting, the real impact of OLED lighting will be in general lighting. The global general lighting market exceeds $90 billion in size, and general lighting is where about one-sixth of the total electricity is consumed. Success in the general lighting market not only brings the most monetary benefits but also will have the most positive impact on the environment.

To succeed in the general lighting market, OLED lighting must be competitive in performance and cost to the existing and upcoming lighting technologies, including the long-established incandescent lamps, fluorescent lamps, compact fluorescent lamps (CFLs), and the upcoming LEDs. Can OLEDs meet the challenge? This is what the paper is trying to answer. We review the status of OLED lighting technology and analyze its potential for future improvements.

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Table 1 Efficacy values of different light sources.

Technology	Efficacy, lm/W
Linear fluorescent lamp (T8)	80–100
Linear fluorescent lamp (T12)	60–80
Circular fluorescent lamp (T9)	60–80
Compact fluorescent lamp (CFL)	65
Incandescent lamp	15
LED (cool white)	208
LED (warm white)	109

2 Efficacy of Competition

Table 1 presents a summary of the frequently quoted efficacy values found from Web sites or product catalogs for the most common lamps. These are very impressive numbers, and they appear to present prohibitive targets for OLED lighting to meet. What is not generally publicized, however, is that these are “bare bulb” numbers obtained using integrating spheres or goniophotometers to measure the total output from these light sources. Because all these lamps are point or line sources with all the light coming from very small areas, they are extremely bright sources. In practical luminaires, fixtures have to be used to cut down the glare. The use of fixtures can cause significant loss of light. Furthermore, the measurements are made under specific testing conditions at some particular temperature, orientation, driving conditions, etc. In actual use, the conditions in the luminaires can be quite different. Because the performance of these lamps is sensitive to these conditions, end users can experience quite different performance from those suggested from Table 1.

Take LEDs as an example. The difference between the efficacy of a source (the LED package) and the efficacy of the luminaire using the source in actual operations can be very dramatic. The specification efficacies for the LED packages are typically measured using a short pulse at a relative low current density. In actual use, the LEDs are on continuously and the current density is usually much higher. These real-life operating conditions in the luminaires cause significant heating of the LEDs. This is particularly true if the LED package and the luminaire do not have adequate heat sinking. Because LED performance is very sensitive to temperature, the performance of LED luminaires can be much lower than that of the LED packages. Figure 1 shows an estimate from the U.S. Department of Energy 2010 R&D Roadmap[1] of the various losses going from a LED package to a LED luminaire. Taking into account all of the five loss mechanisms, we see that the efficacy of the LED luminaire is only 32% of the efficacy of the LED package.

The U.S. Department of Energy recognizes the significance of this issue and has been promoting the use of luminaire-based performance. To this end, the U.S. Department of Energy has set up a CALiPER program that tests and reports commercially available luminaires. Figure 2

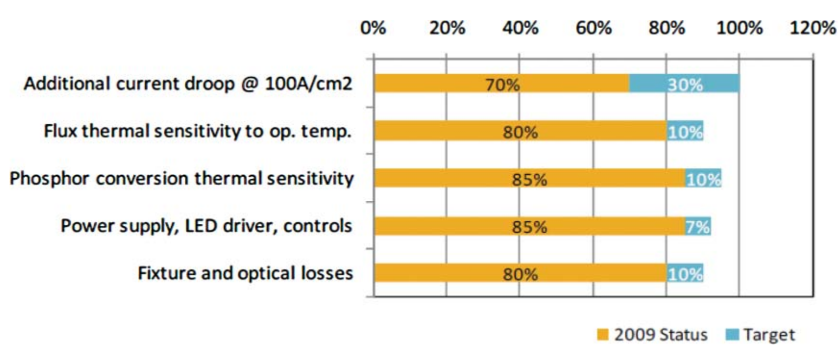


Fig. 1 Sources of loss in a phosphor-converted LED luminaire (Ref. 1).

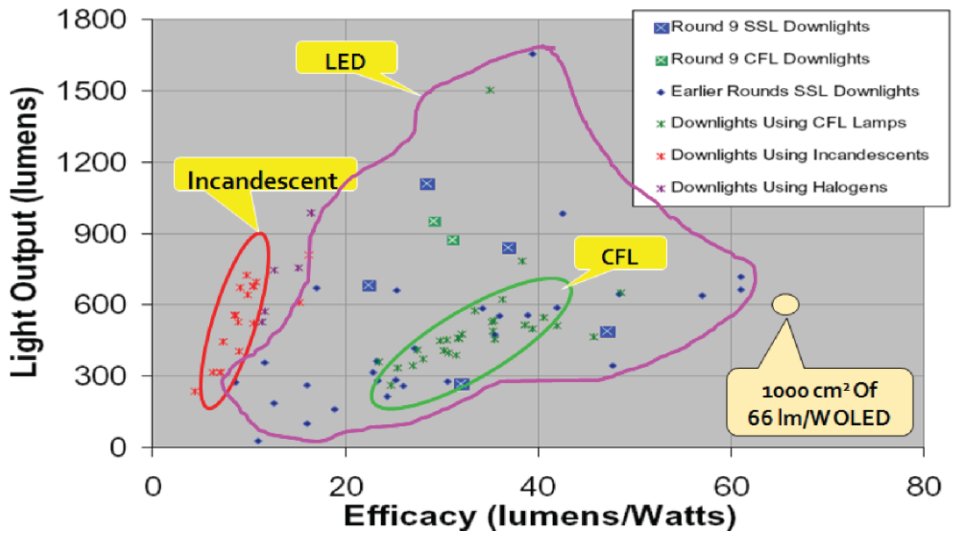


Fig. 2 Efficacy of commercially available down-lights from DOE CALiPER Round 9 Summary Report. Also included is a data point for a 66 lm/W OLED device to be discussed later. The total light output from an OLED device depends on its size. A 1000-cm^2 OLED operating at 2000 cd/m^2 luminance gives ~600 lumens of total light output.

is a summary chart from the CALiPER Round 9 Summary Report[2] of down-light luminaires. Included in the study are ceiling lights, track lights, and recess lights made from incandescent lamps, CFLs, and LEDs. The horizontal axis shows the efficacy, and the vertical axis shows the total light output in lumens of the tested luminaires. The chart shows that the efficacy of the luminaires based on incandescent lamps is about 5 to 10 lm/W, and that based on the CFL is between 25 and 45 lm/W. The LED-based luminaire shows a much bigger range of performance. Some LED-based luminaires are even as inefficient as those based on incandescent lamps. This big range is clear evidence that LED luminaire design can greatly affect its performance.

3 Efficacy of OLEDs—Status

There has been rapid progress in OLED device performance. Figure 3 is a compilation of some better performing white OLED devices reported in the literature. The data points are plotted on the 1931 CIE x,y color chart against the eight DOE Energy Star tolerance quadrangles.[3] The color coordinates must fall within one of the eight tolerance quadrangles for the lighting devices to be Energy Star compliant. This color requirement not only guarantees the color quality of the luminaires, it also ensures a fair comparison of the luminaire efficacy. Because color and efficacy are correlated, the CIE-y coordinate is, in particular, directly correlated to the efficacy. Devices having high CIE-y values have exaggerated efficacy numbers, but they are not suitable for general lighting applications.

Each data point in Fig. 3 is labeled with an abbreviation for the name of the company reporting the data and the reported efficacy value. The triangles represent all-phosphorescent devices, and the squares represent hybrid devices. Hybrid devices typically have a fluorescent blue emitting layer and either a phosphorescent orange or a phosphorescent green/red double emitting layer. Symbols with green color designate devices having a “thin” light extraction enhancement layer in the form of a coating or a laminated thin foil; those with magenta color designate devices using “bulk” light extraction schemes in the form of prisms or hemispheres. The latter also include those using high-index glass substrates. The bulk extraction enhancement schemes and the high-index glasses are considered not practical from a cost point of view.

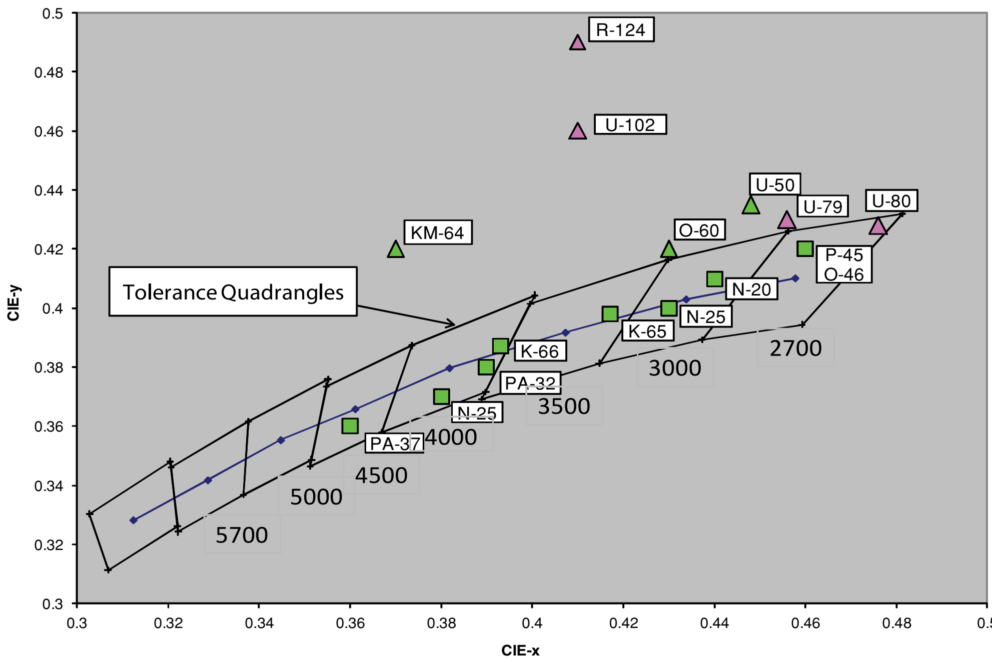


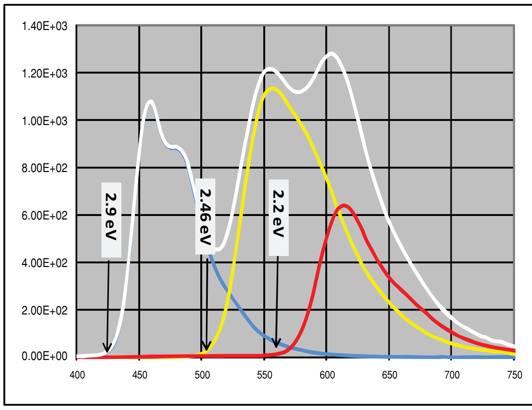
Fig. 3 Better performing white OLED devices. Each data label comprises a company name abbreviation and the efficacy value of the reported device. PA: Komoda *et al.* (Ref. 4); U-50, U79, U-80: Levermore (Ref. 5); N: Birnstock *et al.* (Ref. 6); KM: Nakayama (Ref. 7); K: Tyan *et al.* (Ref. 8); R: Reineke (Ref. 9); P: Bertram (Ref. 10); O-48: Hunze *et al.* (Ref. 11), U-102: D'Andrade *et al.* (Ref. 12).

The best Energy Star color-compliant device appears to be the 66 lm/W hybrid device reported at the Society for Information Display Conference in 2009 (Ref. 8) (the SID 09 Digest showed only 56 lm/W, but an improved 66 lm/W device was reported at the conference). The OLED lighting device is unique in that it is naturally a large-area diffused light source. It does not need any fixtures to cut down the glare or to direct the light and hence suffers little or no fixture loss. Because the power is applied over a large area, the temperature rise is minimal. In fact, in most cases, the reported performance numbers are measured at the specified luminance under steady-state conditions already, including the temperature rise. The performance of the OLED-based luminaires is therefore expected to be very close to that of the OLED devices, except for the possible 10–15% loss due to the inefficiency of the driver, which is normally included in calculating the efficacy of the luminaires. The 66-lm/W data point has been added to Fig. 2 to compare against luminaires using other lighting technologies. Even considering the potential loss in efficiency from the driver/power supply, the OLED-based luminaires are already very competitive in efficacy against luminaires using other lighting technologies.

4 Efficacy of OLEDs—Theoretical Limit

How much more efficacious can OLEDs be? What is the theoretical limit of OLED efficacy?

The white light from an OLED lighting device is generated by combining light from two or three colored emitters. The desired Energy Star compliant color is achieved by selecting proper emitters at proper ratios. Knowing the spectra of the individual emitters, the total light output per input current (lm/A) can be computed. For example, the three selected emitters in Fig. 4 can be combined to form a 4000-K CCT (correlated color temperature) white emitter by adjusting the ratio to have 26.6% of the photons in the blue emission, 49.3% in the green emission, and 24.1% in the red emission. For a single-stack all-phosphorescent device, the total internal quantum



(a)

	Phosphorescent Single Stack	Hybrid Double Stack
CCT, K	4000	4000
Blue Photon %	26.6%	36.2%
Green Photon %	49.3%	67.0%
Red Photon %	24.1%	33.3%
IQE	100.0%	136.0%
lm/A	721.7	984.8
Voltage, V	2.9	5.4
Extraction η	100.0%	100.0%
EQE	100.0%	136.0%
lm/W	249	184

(b)

Fig. 4 (a) Emission spectra of the individual emitters in a 4000-K white OLED device and (b) the estimated maximum efficacy of a phosphorescent single-stack device and a tandem hybrid device.

efficiency (IQE) can theoretically reach 100%. If the extraction efficiency is also assumed to be 100%, the total light output can reach 721.7 lm/A. For a double-stack hybrid device having a fluorescent blue emitting unit and a phosphorescent blue/red double emitting unit, the IQE of the phosphorescent green/red unit can reach 100%. The IQE of the blue fluorescent emitting unit has to reach 36% in order to achieve the proper photon ratio for the 4000-K white emission. Although this is higher than the conventional considered limit of 25% for fluorescent emitters, recent evidence[13,14] has shown that the IQE of fluorescent emitters can be as high as 40% due to additional singlet emission from triplet-triplet annihilation. Assuming again 100% extraction efficiency, the maximum light output is 984.8 lm/A. The theoretical limit of OLED efficacy can be computed by dividing the maximum light output by the minimum operating voltage. A reasonable estimate of the minimum voltage is the highest photon energy in the emission spectrum. For the all-phosphorescent single-stack device and for the fluorescent blue unit in the hybrid device, this value is $\sim$2.9 V. For the phosphorescent G/R unit in the hybrid device, it is $\sim$2.46 V. Thus, the theoretical limit of efficacy for the all-phosphorescent single stack device is $721.7/2.9 = 249$ lm/W and that for the hybrid double stack device is $984.8/(2.9+2.46) = 184$ lm/W. These values do not depend strongly on the color temperature selected for the calculation.

As expected, an all-phosphorescent single-stack device has much higher theoretical efficacy than a hybrid device. Yet most of the better performing Energy Star color-compliant devices in Fig. 3 are hybrid devices. This is because a high-efficiency, stable, true blue phosphorescent "emitting system" is still not readily available. The term "emitting system" is used here because, as will be shown in the following discussions, what is needed is more than an efficient blue emitting dopant.

Experimentally, as shown in Fig. 3, the best Energy Star color-compliant tandem hybrid device[8] is 66 lm/W and the best all-phosphorescent single-stack device[5] is 80 lm/W. These values are only 36% and 32%, respectively, of the corresponding theoretical limits. For the hybrid device, the 5.7 V observed voltage is close to the theoretical 5.4 V value; thus, voltage is not the culprit. The observed external quantum efficiency (EQE) at 54.6%, however, is only $\sim$40% of the 136% theoretical value. EQE is a product of the IQE and the extraction efficiency. Because there is no reliable way to measure or calculate either of these quantities independently, we cannot be certain which of these two quantities is causing the low EQE. As the discussion that follows shows, however, it is most likely the extraction efficiency.

For the all-phosphorescent device, the observed EQE is again $\sim$42% of the theoretical value. Because this device used an external extraction enhancement scheme (EES) instead of the internal extraction enhancement scheme (IES) used for the hybrid device, the extraction efficiency is likely to be lower and the IQE is likely to be closer to the theoretical value than those in the hybrid device. For this device, it is even more likely that the low extraction efficiency is accounted for most of the gap between the theoretical EQE and the experimental EQE. In addition to the extraction loss, the observed 3.8-V drive voltage is $>30\%$ higher than the theoretical value. This high voltage is likely due to the limited selection of host, charge injection, and charge transport materials having high-enough triplet energy to be compatible with the blue phosphorescent emitting material. To further improve the performance of all-phosphorescent devices, the phosphorescent blue emitting system including the emitting dopant materials, the host, and the charge injecting and transporting materials needs to be improved.

5 Light Extraction Efficiency

Because of the high index of the emitting organic layers ($n = 1.7$–1.9), most of the light generated in the OLED devices is trapped in the organic/ITO layers and in the substrate due to total internal reflection. The trapped light cannot get out of the device to do useful work and is eventually absorbed and wasted as heat. Using classical ray optics for an isotropic emitter a rough estimate is that only $1/2n^2$ of the generated light can be emitted into the air. This is $<16\%$ if the index is 1.8, the value of some commonly used emitters. More advanced model calculations showed that interference due to the multilayer structure of the OLED can have strong inference on the light emission. It has been shown that by optimizing the layer structure, the emitted light can be increased over the $1/2n^2$ value, but it still accounts for a small fraction of the generated light. Increasing the fraction of the emitted light (the extraction efficiency) therefore offers the best opportunity for improving the OLED performance.

In general, light generated by the emitter is distributed into four modes. The air mode is the portion of light emitted into the air that does useful work. The percentage of the air-mode photons to the total generated photons is defined as the extraction efficiency. The substrate mode is the portion of light that is trapped in the substrate. Organic/ITO mode is the portion of light that is trapped in the organic/ITO layer stack. There is also a "mode-4" light that accounts for the light coupled to the surface plasma, absorbed within the layer structure, and the losses to other possible causes. The nonair modes are eventually lost to absorption by the organic layers and the electrode layers. The distribution of light in the different modes has been calculated using various models. It has been our observation that the different modeling studies give qualitatively similar results but can differ significantly on quantitative predictions, mostly due to difference in estimation of the mode-4 light. Because there is no easy way to experimentally verify the validity of any of these studies, these models cannot be used to reliably predict the absolute value of the emitted light or the extraction efficiency. Empirically it is only possible to measure the EQE, which is the number of photons emitted per injected electron. EQE is a product of the IQE and the extraction efficiency. Because it is also not easy to measure IQE independently, we cannot deduce the extraction efficiency from the measured EQE.

The importance of light-extraction efficiency enhancement (LEEE) has been recognized for some time,[15] and there have been many LEEE schemes reported in the literature. Most reports use the "enhancement factor" to gauge the effectiveness of their LEEE scheme. The enhancement factor is the ratio of the EQEs for two devices with otherwise identical structures, one with and one without the LEEE. The enhancement factor, however, is a very misleading quantity to use and it can greatly exaggerate the effectiveness of the LEEE.[16] Because of the multiple interference effect in the OLED structure that has many optical interfaces, distribution of light in the various modes depends strongly on the device structure. The distance between the emitting layer and the reflecting electrode layer is particularly important because the strongest interference is between the directly emitted light and the light reflected from the electrode. The air-mode light can be greatly reduced if this distance is chosen to cause destructive interference between the directly emitted light and the light reflected from the electrode. The effectiveness of an LEEE can be greatly exaggerated if this device is used as the control because even a small increase in the air-mode light can result in a big enhancement factor. To more reliably assess the effectiveness of LEEE, the control device must be optimized for maximum air-mode light emission. In other words, the enhancement factor should be calculated by comparing the best device with the LEEE to the best device without the LEEE. Most likely, the two devices would have different layer thicknesses. For the control device, the layer thicknesses should be optimized for maximum air-mode light; for the test device, the layer thicknesses should be optimized for maximum total extracted light. Unfortunately, this procedure has seldom been followed in the literature. To make the situation worse, the device performance is generally very poor in these reports, which makes it even more difficult to judge the effectiveness of the schemes. These points should be kept in mind in the following discussions.

Some of the prior art used bulk extractors, such as a hemispherical lens[9] or a prismlike structure.[17] Proper use of such bulk structures over a small area OLED device can indeed effectively extract the substrates mode as well as the air mode light by avoiding the total internal reflections at the substrate–air interface. If a high index substrate is used, then it can potentially extract the organic/ITO mode light as well. Using a hemispherical lens and a high-index substrate, Reineke *et al*.[9] reported a 124 lm/W white OLED device. Although the efficacy value was inflated because the color was too yellow (shown as the R-124 data point in Fig. 3, the CIE-y coordinate was high), the 46% EQE was one of the highest ever reported. It suggested an extraction efficiency of at least 46%. The extraction efficiency could have been higher because the IQE was most likely $\ll$100%. These bulk extractors are useful in confirming that there is indeed a large amount of trapped light that can be harvested. They are, however, too expensive and physically too bulky to be useful for practical large-area OLED lighting panels.

The more practical schemes use a coating or a laminated foil over the OLED devices. These "thin" schemes can be divided into two categories. The external extraction schemes (EES)are applied over the outside surface of the transparent substrate. Included in this category are roughened substrate surfaces, microlens or scattering films,[18–20] photonic crystals, etc. The EES can be formed after the OLED is completed, and hence, it is simple to apply. The effectiveness of EES is limited, however, because EES cannot extract the organic/ITO mode or the mode-4 light.

The internal extraction schemes (IES) are applied between the substrate and the transparent electrode or between the two electrodes. These schemes can potentially also extract the organic/ITO modes of light and hence are much more effective than EES. It is technically much more difficult to implement, however, because whatever is applied next to the organic layers can damage the OLED devices, mechanically causing shorts, or chemically causing degradations. Lee *et al*.[21] reported a 50% improvement in extraction efficiency using a photonic crystal structure. An attempt to use nanoporous anodized aluminum as IES also showed only 50% improvement in extraction efficiency,[22] which was only comparable to the best results reported using EES. Using 2-D photonic crystal structures, Kim *et al*.[23] were able to demonstrate an improvement of 85% in normal angle output over a conventional device. Because of the periodic structure of the photonic crystal, however, the emitted light showed pronounced angular dependence. The overall enhancement factor integrated over all angles was not reported. For general lighting applications, the Energy Star specification[3] has stringent requirements on the angular dependence of color. Clausen *et al*.[19] reported an IES using a plastic film embossed with periodic features and back filled with a high-index coating. It reported an on-axis brightness two times that of the control. The angular integrated light output could be less enhanced because of the strong angular dependence favoring on-axis emission. The angular dependence may also cause a shift in color that make the OLED unsuitable for general lighting applications. Chang *et al*.[24] recently reported an OLED device incorporating a spin-coated polymer layer with imbedded TiO_2 scattering particles as IES. In this work a near doubling of EQE due to the enhanced light extraction efficiency was reported. Nakamura *et al*.[25] reported an IES using a scattering structure based on high-index glass and achieved an illumination 1.8x that of the control. In both cases, the control device was not well characterized. In either case, there was no clear evidence that the IES actually was extracting the organic/ITO mode light. In Chang's

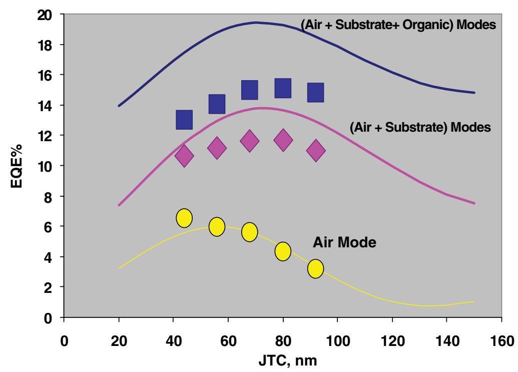


Fig. 5 Comparison of experimentally observed EQE for the devices without the extraction enhancement (yellow), with EES (magneta), and with IES (blue) with the model calculations. The horizontal variable is JTC (junction-to-cathode) distance.

case, for example, the low index matrix used for the IES layer likely prevented the organic/ITO mode light from interacting with the scattering particles.

Tyan *et al*. reported EES and IES enhancement structures that utilized the principle of scattering to frustrate the total-internal-reflection and thereby allow the otherwise trapped light to emit into the air.[26] Comparing to an optimized control device, the application of EES resulted in an 80% improvement in EQE and the IES improved the EQE by 130%. Figure 5 shows the observed EQE of the three types of device as a function of the distance between the emitting layer and the reflecting electrode layer. Also plotted are the model calculated results with the calculated air-mode light fitted to the data of the control devices to get around the issue of unknown IQE. Figure 5 shows that the EES was able to extract >80% of the air-mode plus substrate-mode light, and the IES was able to extract >75% of the air, substrate, and organic/ITO modes of light. These high values suggest that the reported EES and IES were already quite efficient. Even with the efficient IES, however, the EQE for the best IES device was only 15.1%. If we assume the IQE were 25%, the conventional limit for fluorescent emitters, then the extraction efficiency would be 60%. If the IQE were 40% with the triplet-triplet annihilation contribution, then the extraction efficiency would be only 37.8%. There is clearly a lot of room for improvement.

The low extraction efficiency is most likely due to the presence of a substantial amount of the mode-4 light. Figure 5 shows that the total non-mode-4 light amounts to ∼19.1% EQE, suggesting that the mode-4 light could be as high as 51.2% of the generated light if the IQE were 40%. Future efforts in light extraction need either to extract or to reduce the mode-4 light in order to achieve significant improvement.

The same EES and IES were later applied to tandem hybrid device[8] and achieved the 66-lm/W performance. The structures of these devices are shown schematically in Fig. 6. The device in Fig. 6(a) was a control device with no additional extraction enhancement; the device in Fig. 6(b) had an EES applied to the outside of the glass substrate; and the device in Fig. 6(c) had the IES applied between the substrate and the transparent anode layer. All three devices had a tandem architecture combining a fluorescent blue emitting unit and a red/green two-color phosphorescent emitting unit. The EIL-2/HIL-1 bilayer in the middle of the tandem structure formed the connector structure, sometimes also called the charge generation structure, which supplied electrons to the fluorescent blue emitting unit below and hole to the phosphorescent unit above. In operation, the current flows through the two emitting units, producing lights simultaneously in these units, which combine to form white light. In addition to the high performance, these devices exhibited a very important behavior as shown in Fig. 7. The charts in Fig. 7 show the EQE, voltage, and CIE-x, CIE-y color coordinates of two series of IES devices plotted against the ETL-1 and the HTL-1 thickness.

Fig. 6 Schematic of three tandem hybrid devices with (a) no extraction enhancement layer, (b) EES, and (c) IES. EIL: electron injection layer; ETL: electron transport layer; HIL: hole injection layer; HTL: hole transport layer; EBL: electron blocking layer; SRL: short reduction layer (Ref. 27).

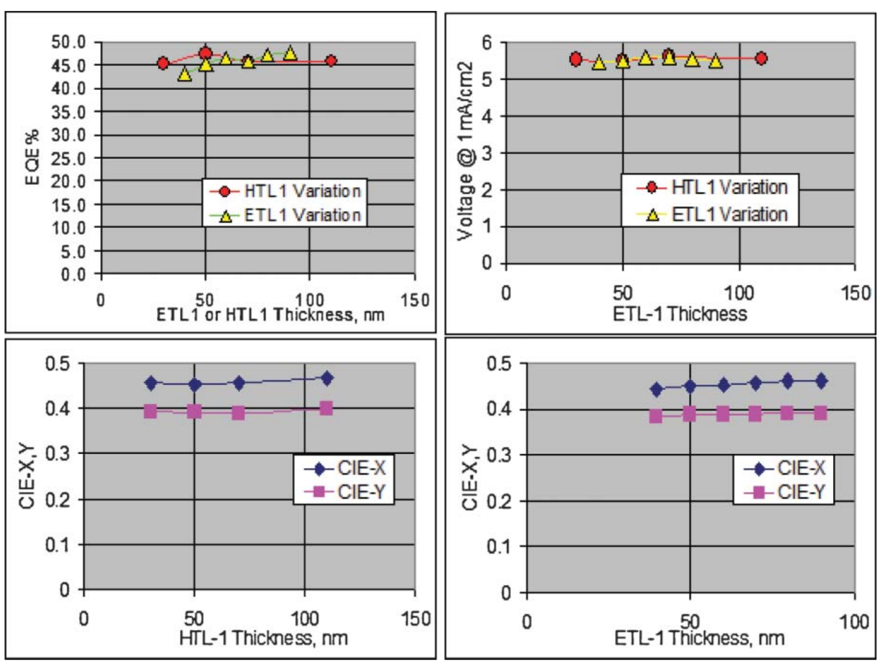


Fig. 7 Dependence of EQE, voltage, and CIE color coordinates of two series of devices each had either the HTL-1 layer or the ETL-1 layer varied over a range.

We can see from these charts in Fig. 7 that all the measured parameters were almost constant over the over wide range of ETL-1 and HTL-1 thickness. This behavior is consistent with model calculations. These calculations show that the air-mode, substrate mode, and organic/ITO modes of light all show strong modulation with the distance between the emitter and the cathode. This modulation is caused by optical interference in the multilayer structure, the strongest interference being that between the directly emitted light and the light reflected from the cathode. The effect of the interference, however, is mostly to direct the light into the different modes. The modulation becomes much weaker when all three modes of light are added together. The absence of dependence of the measured parameters on ETL-1 and HTL-1 thickness is strong evidence that the IES is able to extract all three modes of light with similar efficiency.

6 Device Lifetime

To position OLEDs as luminaires, they have to have the lifetime expected of a luminaire. A conservative figure is 15 years. There are two well-known degradation mechanisms for OLEDs: the dark spot formation and the gradual decrease of performance with current passing through the device. The former takes place all the time, independent of whether the device is operating and therefore impacts the shelf life. The latter only takes place while the device is operating and therefore determines the operating life.

The dark spot is formed by the penetration of moisture through defects in the cathode, causing degradation of the cathode-organic interface.[28,29] The degradation resulted in a high-resistance region around the defect diverting the current away from the region, preventing it from emitting light. As the moisture diffuses latterly along the interface, the dark spot continues to grow in size uniformly in all directions, resulting in its circular shape. The growth of dark spots has serious impacts on OLED displays, reducing their visual quality. For lighting applications, however, some degrees of dark spot formation might be tolerable because the appearance of dark spots in lighting panels is less objectionable. This is particularly true for OLED panels having a scattering-type light extraction scheme that makes the dark spots even less visible. With excess dark formation, however, the dark spots can take so much area that they effectively increase the current density in the remaining area of the device, causing accelerated degradation due to operation. For devices using glass substrates, the dark spots problem seems to have been much resolved, as evidenced by the success of the widely available OLED display devices, by encapsulating the device with a glass or metal backing, using edge seal and desiccant. For devices using plastic substrates or using thin-film encapsulation, adequate protection of OLEDs against moisture lasting over the expected lifetime of a luminaire has yet to be demonstrated.

The degradation of OLED devices due to operation is well documented and appears to be caused by chemical degradation of the organic materials.[30–33] Phenomenologically, its dependence on the operating current follows:

$$I^n Tx = \text{const.} \tag{1}$$

where I is the operating current and Tx is the lifetime. For example, $T50$ is the time to reach a 50% reduction in output, $T70$ is the time to reach a 30% reduction in output, etc. The exponent n is a number that varies with device design, but is typically $\sim$1.5. Because the luminance from an OLED device is proportional to the operating current, a similar relationship exists for the lifetime dependence on luminance.

Equation (1) suggests that the lower the luminance an OLED panel operates the longer its lifetime is. Lower luminance lowers the glare, which is also desirable. The cost of OLED panels, however, is proportional to its area. Operating at lower luminance means a larger OLED panel is required to generate the same total amount of light, hence the cost of light becomes higher. A compromise is therefore necessary. The DOE Multi-Year Program Plan[1] suggests OLED panels to operate at a luminance of 1000 cd/m^2, we suggest operating the panels at a luminance of 2000 cd/m^2 instead. 2000 cd/m^2 is the average luminance level of fluorescent troffers[2]. At

Table 2 Recently reported OLED device lifetime values. All numbers in blue were calculated using the simple formula that the lifetime at 1000 cd/m^2 is three times the lifetime at 2000 cd/m^2, and T50 is three times T70. The UDC numbers were calculated using these formula based on the reported T70 value at 1000 cd/m^2.

Company	T50 hours 1000 cd/m^2	T50 hours 2000 cd/m^2	T70 hours 2000 cd/m^2	Refs.
Panasonic Electric	40,000	13,333	4,444	(Ref. 4)
Novaled	60,000	20,000	6,667	(Ref. 6)
UDC	75,000	25,000	8,333	(Ref. 5)
LG Display	130,000	43,333	14,444	(Ref. 34)
Kodak	125,000	41,667	13,889	(Ref. 35)

this luminance level, a 1000 cm^2 of OLED panel, similar in size to the common ceiling lights, generates ∼600 lms of light, somewhat above the average light output of down-light luminaires (Fig. 2). Using Eq. (1) and a typical n value of 1.5, lifetime measured at 2000 cd/m^2 is roughly one-third of that measured at 1000 cd/m^2. Operating at any higher luminance will result in much lower lifetime and too much glare, operating at anything lower will result in much higher cost for OLED lighting making it less competitive.

It has become customary to report OLED performance at 1000 cd/m^2 and the lifetime as T50. It has been suggested that T70 is more appropriate for lighting applications because traditional light sources such as incandescent and fluorescent lamps show <30% luminance degradation before they fail. There is the concern that the use of T50 would cause nonuniform lighting appearance if a bank of luminaires is used and some of them having replaced bulbs and others having aged bulbs. It is debatable, however, whether such concerns are valid under the scenario that OLED panels are serving as luminaires with such long lifetimes that the traditional "replacing bulb" model no longer is meaningful.

There has been great recent progress in the reported OLED lifetime. Table 2 shows some of the recently reported values. Most of the values were reported as T50 at 1000 cd/m^2 initial luminance. From these values, the T50 at 2000 cd/m^2 initial luminance was estimated using the 3× rule discussed above. For typical OLED devices that we studied, the T50 lifetime is about three times that of the T70 lifetime. The T70 values in Table 2 at 2000 cd/m^2 were calculated using this simple relationship.

For residential applications, the average operating time is ∼5 h/day; for commercial applications, it is 10 h. A 15-year lifetime translates to about 27,000 h and 54,000 h of operation, respectively, for the residential and commercial applications. Data in Table 2 suggests that the state-of-the-art OLED devices already have enough lifetime for commercial applications at 1000 cd/m^2 if 50% luminance depreciation is allowed. A 4× improvement is needed, however, if the target is 30% luminance depreciation at 2000 cd/m^2 for commercial markets.

Improvement in lifetime can be achieved not only through improvements in materials and device architectures, but through efficacy improvements as well. An improvement in efficacy means less current is required to achieve the same light output, which translates directly into a significant improvement in lifetime. It is anticipated that a significant portion of the required 4× lifetime improvement will be achieved through efficacy improvements alone. Efforts in light extraction and blue phosphorescent emitting system will therefore have the double benefits.

In addition to improving the fundamental lifetime of OLED devices, practices such as occupancy sensing, aging compensation, and preaging (burn-in) can all be used to improve the effective lifetime of OLED panels. We feel optimistic that OLED lighting will have adequate lifetime to serve as luminaires.

7 Cost

The commercial success of OLED lighting depends on whether it can be cost competitive against other lighting technologies. For general lighting, OLED is a nature fit for the ceiling-mounted

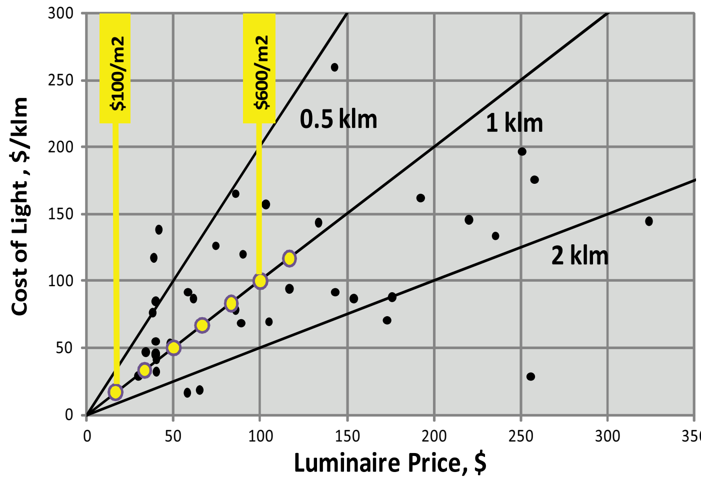


Fig. 8 Cost of residential-grade ceiling lights based on fluorescent and compact fluorescent lamps. Source: National Lighting Product Information Program Specifier Reports (Ref. 36).

indoor luminaire applications. Luminaires in this category consume more electricity than any other indoor luminaires in both the commercial and the residential applications. Although the commercial market is mostly served by fluorescent sources, the residential market is still dominated by incandescent lamps. The market size and energy savings potential in this segment are both substantial.

There are three grades of luminaires in the U.S. lighting market: specification, commodity commercial, and commodity residential. The commodity residential is the most price-driven of the three grades. Commodity residential grade luminaires offer low price, have unsophisticated optical and thermal designs, are made of inexpensive materials, and therefore represent the most difficult to compete against in cost. A National Lighting Product Information Program Specifier Report[36] studied 42 residential-grade energy-efficient residential-grade luminaires based on fluorescent and compact fluorescent lamps. The catalog prices of these luminaires are shown in Fig. 8. The horizontal axis shows the luminaire price; the vertical axis shows the cost of light in dollars per kilolumen (klm), defined as the price of the luminaires divided by their total light output. Also shown are three straight lines representing the luminous output at 0.5, 1.0, and 1.5 klm. Even for the residential grade, there is a wide distribution of prices, with the luminaire price ranging from about \$30 to over \$300 and the cost of light ranging from about \$16/klm to about \$250/klm. OLEDs are a near Lambertian light source, and a luminaire operating at 2000 cd/m^2 produces ~6 klm/m^2 of light. An OLED panel producing 1 klm of light requires ~0.17 m^2 of area (~41×41 cm). If the OLED luminaire could be sold at \$100/m^2, then the luminaire cost would be \$17, lower than all the current commercially available luminaires. The cost of light at \$17/klm price almost matches the cheapest of them. Even at \$600/klm, the luminaire price and the price of light would still be about average of the current commercially available luminaires.

OLED lighting is still under development with a few companies just gearing up for pilot production using equipment designed for OLED display manufacturing. There are therefore no meaningful manufacturing cost numbers. Recently, the U.S. Department of Energy published the Solid-State Lighting Research and Development: Manufacturing Roadmap,[37] which includes a cost projection for OLED lighting panels, as shown in Table 3. According to this projection the cost of OLED lighting panels will break through the \$100/m^2 barrier when large-scale manufacturing begins, projected to be in 2015. Although this is the manufacturing cost and not the retail price shown in Fig. 8, it does appear that OLED lighting can be first-cost competitive, even with the residential-grade ceiling light of other lighting technologies. With its improved efficacy,

Table 3 Projected cost of OLED lighting panels source: Solid-State Lighting Research and Development: Manufacturing Roadmap (Ref. 37).

	Year		
Stage	**2011**	**2013**	**2015**
Depreciation ($/m^2)	420	160	30
Labor ($/m^2)	305	45	5
Other operations ($/m^2)	70	20	4
Organic Materials ($/m^2)	30	15	10
Substrate ($/m^2)	6	6	6
Electrodes ($/m^2)	20	15	10
Light extraction ($/m^2)	20	15	10
Encapsulation ($/m^2)	10	8	5
Other materials ($/m^2)	20	15	10
Total cost ($/m^2)	900	300	90
Total cost ($/klm)	300	50	9

color quality, and other desirable features, OLED lighting can most likely be positioned in the premium luminaire market and command even higher prices than the fluorescent luminaires.

Most of the price decrease in this chart is achieved through reduction of depreciation and labor costs as a result of manufacturing scale up. It is anticipated that the cost of OLED light lighting will continue to decrease as demand increases and manufacturing technology continues to improve.[4,38,39]

8 Summary

OLEDs are unique in that they are naturally large-area diffuse light sources that do not need any additional fixtures to cut down the glare or to distribute the light. They are almost luminaires and should be positioned as luminaires in the marketplace. Compared to luminaires using other lighting technologies, OLEDs are already competitive in efficacy and there is potential for still further improvement. As luminaires, the lifetime of OLEDs might need to be improved. Improving the efficacy will automatically improve the lifetime, and improving the way OLEDs are being used can lead to effectively a longer lifetime as well. OLEDs can be cost effective as luminaires when volume manufacturing begins and with improved manufacturing technology.

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