Light extraction efficiency enhancement on organic light-emitting device by microlens array attachment: a systematic approach

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Abstract

A microlens arrays formed by thermal reflow method is attached to an OLED device and the light extraction efficiency which includes luminance and power information is determined by adjusting the area ratio and the height ratio.

1. Introduction

The total electroluminescence (EL) efficiency of OLED device is the product of internal quantum efficiency and the external coupling efficiency [1]. The internal quantum efficiency can be raised to nearly 100% [2]. But how to increase the external quantum efficiency is still a main issue. Due to total internal reflection (TIR) occurring between glass substrate and air, only about 20% to 30% of the generated light can propagate into the air. Most of the light is lost due to wave-guiding and TIR in the glass substrate and ITO layer [3]-[4]. Nowadays there are various methods to enhance the external coupling efficiency [5]-[7]. Among them, attaching a microlens array on OLED is one of the useful methods.

In this paper, we present a systematic method to evaluate the light extraction efficiency and the design rule for using a microlens array. It shows that area ratio and height ratio are the most significant parameters of microlens array. Important design rules can be deduced from quantitative analysis.

2. Results

The microlens array we used is formed by thermal reflow method [5]. We attached different types of microlens array to glass substrate of OLED by using silicon oil for index matching. We perform the numerical simulations with the optical software LightTools™. A simulation model is built up based on the following facts. Since the dipole distribution in an OLED is randomly oriented that leads to spontaneous emission, it is reasonable to assume the emitting light distribution is isotropic emission in organic layer. Metal cathode at the bottom reflects light and we can simply assume all lights propagate into ITO layer. Some light can successfully go through the ITO layer and finally escape from the glass substrate. Some light is trapped in the ITO layer and glass substrate depends on incident angle at the interfaces.

In our simulation, we assume the light source is at the interface of electron-transport layer (ETL) and hole-transport layer (HTL). Electrons and holes transport in HTL and ETL under electrical excitation. The holes and electrons recombine to emit light at the interface of these two layers. Both thickness of HTL and ETL are assumed to be 60nm and the respective refeactive indices are 1.8 and 1.7. For simplification, we assume that the emitting wavelength to be 550nm. Metal cathode is used as for electrons provider in the OLED structure. In our simulation, we assume that an ideal reflector instead of metal cathode layer is located at the bottom surface of ETL and hence its reflectivity is 100%. This makes no difference in electrical property while we are concerned about the optical property. Indium-tin-oxide (ITO) plays a role as holes provider in the OLED structure, it is a transparent thin film on top of HTL with 110nm in thickness and its refractive index is assumed to be 1.9 for the specific emitting wavelength. Finally, Glass substrate is added to the simulation model on top of the ITO. The thickness of glass substrate is 630 micron which is much larger than the other layers in our simulation model and it dominates the size of OLED device. The material for glass substrate is assigned to BK7 of which refractive index is about 1.5. These layers we mentioned above are assumed 5mm in both lateral dimensions.

Light propagation is described as millions of rays emitted from light emitting area and experiences only TIR or transmission behavior in each layer. In our simulation model, we have neglected absorption, scattering, and birefringence, etc.

After finishing the OLED model, we setup a far field receiver which is 2 cm far from the center of top surface of glass substrate to record intensity, power, and luminance information.

To verify the validity of our simulation model, we compare our results with those of the previously published work. S. R. Forrest *et al.* [8] demonstrated that only 17.5% of emitted light can be coupled out from glass substrate into air by using a simple ray-optics model. They also showed that the ratio of the optical energy transmitted into any specific layer with respect to the total emitted energy is only affected by the refractive index of these two layers [9]. From the formula and calculated results in [8], we can compare our simulation result with theris.

In our simulation, 18.2% of generated light can be coupled out from glass substrate into air, and 51.3% of generated light can be coupled out from ITO into glass substrate. If we can get rid of the limitation of glass substrate the possible maximum enhancement of out coupling efficiency is 0.513/0.182=2.8. These results closely match the previous study in [8]. We can further confirm our result with intensity distribution in [4]. In that paper, they used a numerical calculation method based on ray-optics and experimental results of the angular distribution of intensity showed normalized to that at the normal direction.

In Figure 1 we show similar results based on our numerical model. In this figure, we take lambertian emitter as comparison with intensity distribution. Under the same assumption, the results in our simulation closely match that one without loss in [4]. Besides intensity distribution in the air, we also record the light intensity distribution in the glass substrate. Compare relative intensity in glass substrate with that in air, we can find that at large angle the relative intensity in glass substrate is larger than that in air. It confirm to the fact that light in glass substrate can not propagate to air when incident angle is larger than critical angle. Thus the intensity distribution in air is smaller than that in glass substrate evidently with the view-angle getting larger.

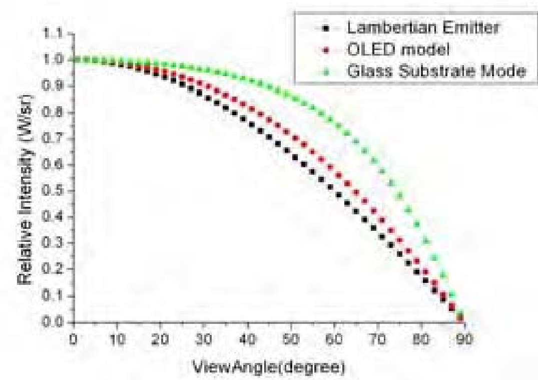


Figure 1 Intensity distribution pattern for OLED model in air, expected profiles of a Lambertian emitter, and intensity distribution pattern in glass substrate. These three intensity distributions are normalized to 1 at zero degree.

Our simulation shows that the intensity distribution in Figure 3 is consistent with that of [4] and only 18.2% coupling efficiency for OLED device without the microlens film, closely to [8]. We demonstrated the validity of our simulation model and made preparation for the following simulation. We will attach microlens array to glass substrate in our model and discuss further about it.

We present a systematic method to evaluate the light extraction efficiency and the design rule for using microlens array. It shows that area ratio and height ratio are the most significant parameters of microlens array. With microlens array attached, TIR at the air/glass interface is destroyed and the light extraction efficiency is enhanced. We conclude the design rules for two important parameters: the area ratio and the height ratio.

(I) Area ratio

The area ratio (A) is defined as the total base areas of microlenses divided by the total area of glass substrate. It stands for the percentage of the glass substrate covered by the microlens array.

From simulation, we will show that intensity distribution is largely affected by the area ratio. We keep the base diameter of lens (=50μm) and lens shape (=hemisphere) the same in the following series, and keep the microlens array to be rectangular arrangement named SR. By changing gaps between two adjacent microlenses from 49 μm, 20.1 μm, 12.6 μm, 7.2 μm to 3 μm, the area ratio is increased from 20.0%, 40.0%, 50.1%, 60.0%, to 69.9%. The formula for calculating area ratio for rectangular arrangement is $A=\frac{\pi}{4}(\frac{D}{D+G})^2$, which can be easily derived by geometric relation. D stands for the diameter of a microlens and G stands for the gap between two adjacent microlenses. In Figure 2 we shows the angular distribution of intensity for different D's and hence A's in the rectangular arrangement.

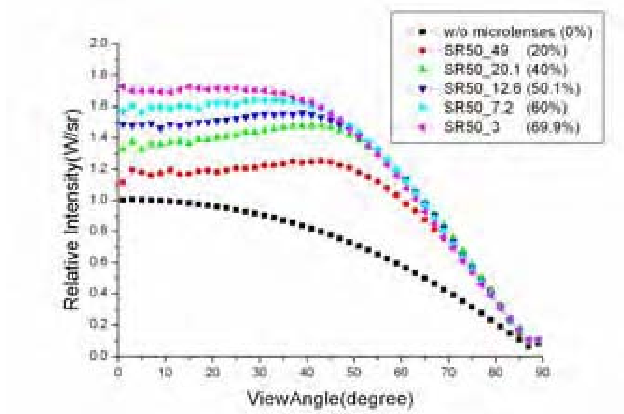


Figure 2 Intensity distribution pattern for OLED model in air, and adding microlens array on it for different area ratio. SR stands for rectangular arrangement, and D stands for diameter of a microlens, and G represents the gap between two microlenses, and A represents area ratio.

Intensity for all cases with microlens attachment is larger than those without microlens films for all angles. And the quantity of enhancement for all cases also varies with angle. Relative intensities are enhanced by increasing A's (i.e. decreasing D's). There is steady increasing of relative intensities with respect to A's at the small angle region. There is relatively large enhancement in the region of [40°,60°]. However, the dependence with respect to A's becomes little for the region of [60°,90°]. To show the importance of area ratio further, we check the results for the series of hexagonal arrangement named SC. By changing gaps between two adjacent microlenses from 56.5 µm, 25.3 µm, 11.4 µm, to 6.9 µm, the area ratio is increased from 20.0%, 40.0%, 60.1% to 70.0%. The formula for calculating area ratio for hexagonal arrangement is $A=\frac{\pi}{2\sqrt{3}}(\frac{D}{D+G})^2$, which can be also derived by geometric relation. We can find that the trend for hexagonal arrangement is same as that for rectangular arrangement by adjusting area ratio in Figure 3.

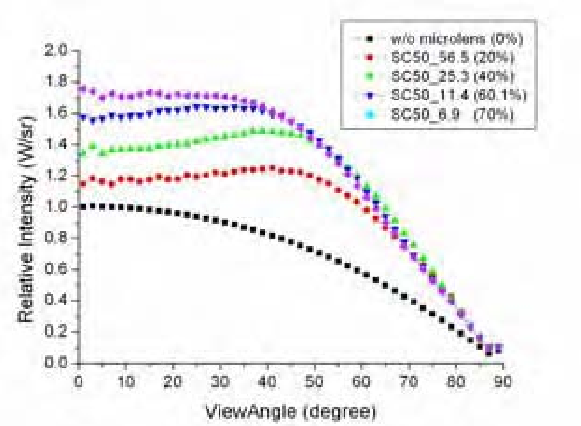


Figure 3 Intensity distribution pattern for OLED model in air, and adding microlens array on it for different area ratio. SC stands for rectangular arrangement, and D stands for diameter of a microlens, and G represents gap between two microlenses, and A represents area ratio.

Luminance calculated by 2° at normal direction for above cases. The luminance enhancement ratio is the ratio of luminance with microlens array attached to that without microlens array attached. Power enhancement ratio is the ratio of total power with microlens array attached to that without microlens array attached. Figure 3 shows that by increasing the area ratio, the luminance enhancement ratio and power enhancement ratio also increase for both rectangular and hexagonal arrangements. Thus we can get higher luminance and power by adding microlenses into array as raising the area ratio close to

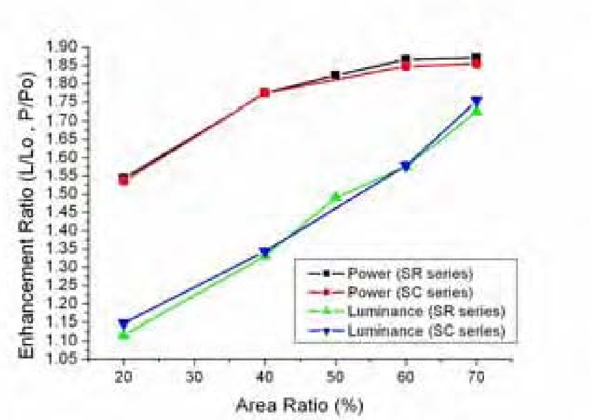
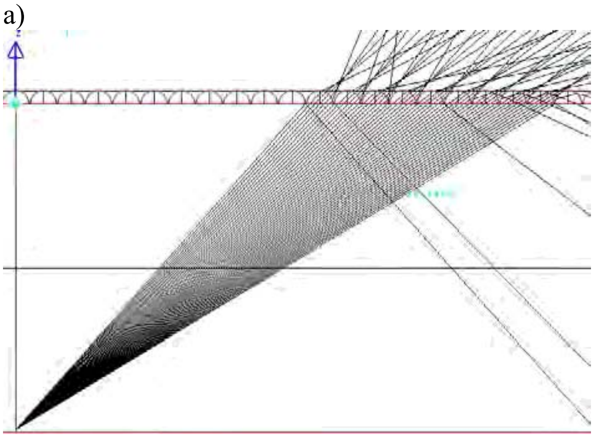


Figure 3 Luminance and power enhancement ratio of SR and SC series for different area ratio, and the parameters L, L_0, P, P_0 are the luminance at the normal direction, luminance at the normal direction without microlenses, total power, total power without microlenses, respectively.

one. The relationship between enhacement and area ratio makes nearly no difference for this two different arrangements. So we can make a conclusion that area ratio is one of important parameters for intensity distribution in spite of the arrangement of microlens array, as long as the microlenses distribute uniformly on the surface of glass substrate.

By illustrating the ray-tracing diagram in Figure 4 we can see the reason why higher area ratio results in larger luminance and power. Obviously, light extracting efficiency closely depends on the density of microlenses on the surface of glass substrate. To destroy the TIR phenomena, it is easily to see that more microlenses help to make more light to escape from the glass substrate. Thus, increasing the area ratio, the power enhancement ratio also increases for both rectangular and hexagonal arrangements. As the area ratio increases up to 70%, the maximum luminance ratio and power ration are raised to 1.87 and 1.75, respectively.

a)



b)

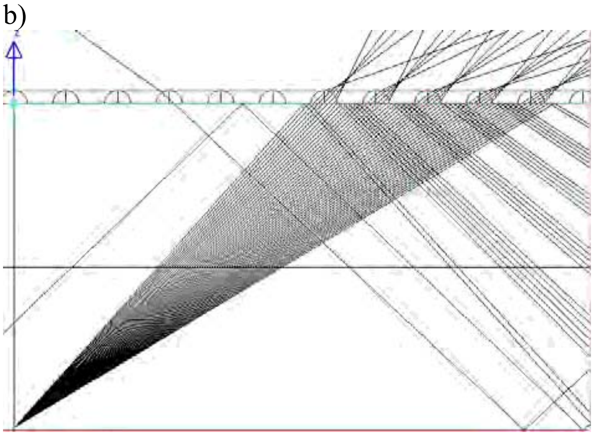


Figure 4 Ray tracing diagram for a) high area ratio (70%) and b) low area ratio (20%) for the same device.

(II) Height ratio

The height ratio is defined as the height (h) of the microlenses divided by its radius of curvature (r). It stands for different shape of microlenses. If the height ratio approaches one, each microlens comes toward a hemisphere. Otherwise, it looks like a thin plano-convex lens.

From simulation, we demonstrate that intensity distribution is largely affected by the height ratio in Figure 5. We keep the base diameter of lens (=10μm) and area ratio (=40%) the same in the following series, and keep the microlens array to be SR in Figure 5 or SC in Figure 6. By changing height of microlens from 5 μm, 4 μm, 3 μm, 2.5 μm to 2 μm, the height ratio is decreased from 1, 0.78, 0.53, 0.4, to 0.28.

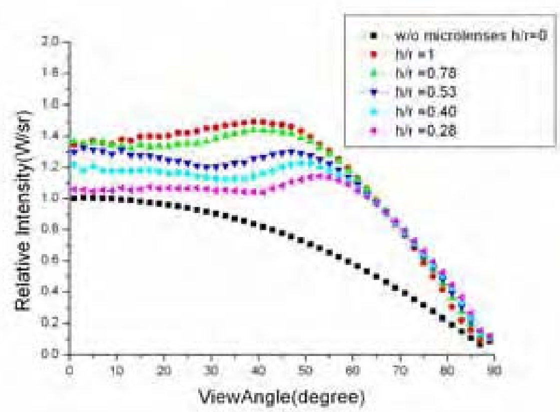


Figure 5 Intensity distribution pattern for OLED model in air, and adding microlens array on it for different height ratio from 1, 0.78, 0.53, 0.40, to 0.28, the arrangement of microlens array is rectangular in this series.

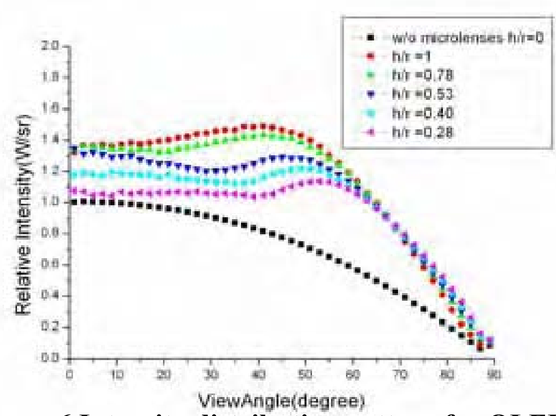


Figure 6 Intensity distribution pattern for OLED model in air, and adding microlens array on OLED for different height ratio from 1, 0.78, 0.53, 0.40, to 0.28, the arrangement of microlens array is hexagonal in this series.

From Figures above, we can confirm that height ratio plays an important role for intensity distribution in spite of the arrangement of microlens array as long as the microlenses distribute uniformly on the surface of glass substrate. As the height ratio increases, the intensity is getting larger. Increasing area ratio affects relative intensity slightly in large angles, but largely in small angles.

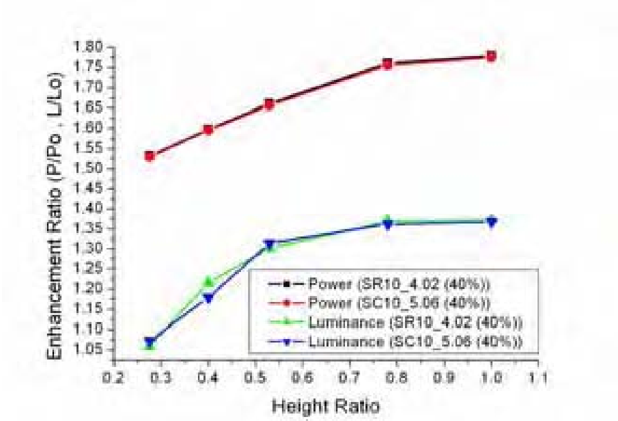


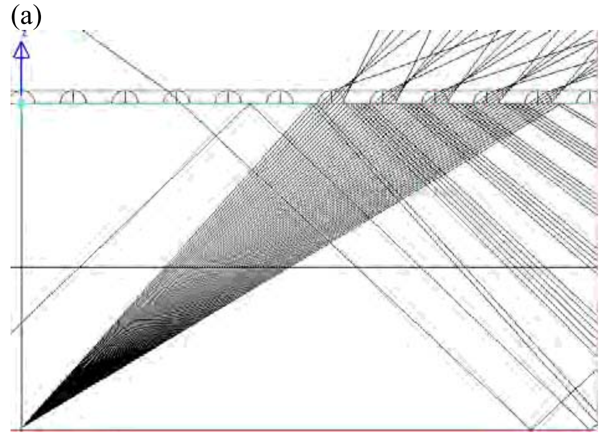
Figure 7 Luminance and power enhancement ratio of SR10_4.02 and SC 10_5.06 for different height ratio, and the parameters L, L_0 P, P_0 are the luminance at the normal direction, luminance at the normal direction without microlenses, total power, total power without microlens, respectively.

From Figure 7 we see that luminance enhancement ratio at normal direction increases as the height ratio increases. Also the total power is largely enhanced with the same trend. They make nearly no difference for SR and SC arrangements.

In Figure 8, we illustrate the ray-tracing diagram to see the reason why the luminance ratio and power ratio increase as the height ratio increases. In this figure, we consider different height of microlens with its base shape the same. The rays starting from the organic layer are incident on the glass/air interface. From Snell's law we assume that incident angle determining the ray transmitted or total internal reflection. As we focus on incident angle larger than critical angle for flat surface, attaching microlens providing another interface with incident angle smaller than critical angle. Larger height ratio stands for larger curvature. So rays have more chance to its incident angle smaller than critical angle. Then it can penetrate through the glass/air interface. The more curve the microlenses are, the more rays bend.When the curvature of microlens approaching to zero, the microlens array acts like a flat plate so that the function of microlens array will disappear. As illustrating in Figure 8, we can see clearly why microlens with small height ratio can not efficiently bend the ray to small angle. Thus we demonstrate the validity of luminance varying with height ratio. We can also discuss on power enhancement by simply judging the quantity of rays in Figure 8.

From above, we find that to keep diameter of microlens' base the same and to increase its height, the luminance is increased. It shows that hemisphere (D=10 H=5) is best choice for light enhancement. As the height ratio increases, the maximum luminance ratio and power ratio are raised to 1.37 and 1.77, respectively.

(a)



(b)

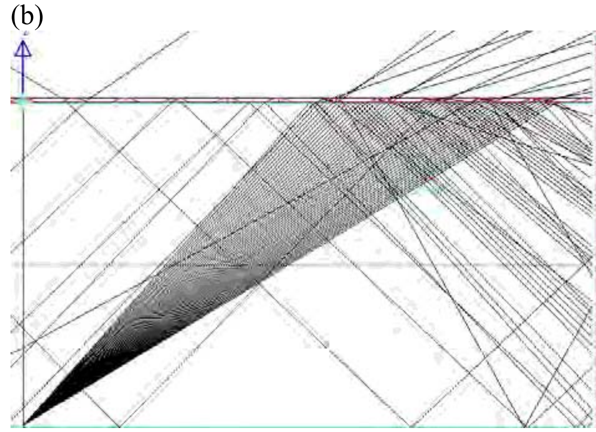


Figure 8 Ray tracing diagram for a) large height ratio (h/r=1) and b) small height ratio (h/r=0.28) for the same device.

3. Conclusion

We have presented a systematic analysis approach to evaluate the light extraction efficiency and design rule for the microlens array. Besides, the simulation results are confirmed by experimental result [10]. The light extraction efficiency can be hugely elevated by using microlens array combined with the OLED panel.

4. References

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