# Chapter 4

## Multi-Zoned Light-Enhancing Layer

To extend the applicable range of planar optics, the structure of planar optics is adjusted to be bottom-input and top-output scheme to fit FPD. In this chapter, an extended type of planar optics, multi-zoned light-enhancing layer (MZ-LEL), is proposed to promote the light efficiency of organic light-emitting diode (OLED) display.

The optical methods used to increase the light out-coupling efficiency of an OLED can be classified into two categories. The first involves the "inside-device" method, such as the mesa-cone structure located inside a bottom-emission OLED to reduce the total internal reflection (TIR).[1] However, its fabrication is complicated. The second category employs the "outside-device" method with an additional "light-enhancing layer" (LEL), consisting of a specific surface profile, such as a hemispherical lens[2] or a micro-lens array. [3],[4] Although the fabrication of this category is rather straightforward, the optical modeling is difficult and the results attained do not support their prediction. For example, one of the micro-lens array methods predicted the enhancement would be 2.3, but only 1.5 was achieved experimentally[3]. This discrepancy may be due to aspects of the simulation modeling and the fabrication margin. Thus, to establish an effective optical model, the application of the Fresnel's equation to the simulation is considered here. A distinct profile of MZ-LEL for precise fabrication and the simulated results which reveal a high level of agreement with the measurements are also presented. Such an MZ-LEL, even when designed for an OLED panel, exhibits the light-enhancing function and can be fabricated by currently available processes. Moreover, the solution to the problems occurring during the lamination of an MZ-LEL and an OLED panel is also presented in this chapter.

## 4.1 Design of MZ-LEL

Although a conventional hemispherical micro-lens array can enhance the out-coupling light efficiency of an OLED, its degree of profile accuracy is difficult to control and this leads to discrepancies in modeling. Therefore, an MZ-LEL with an explicit profile comprising a mesa zone and at least one inclined zone, as illustrated in Fig. 4-1(a), is proposed. Such a profile can be meticulously fabricated using well-established procedures and with little scope for deviation.

The objective of an MZ-LEL is to supress the TIR effect and to extract light trapped in the top stratum of the OLED. The main parameters of an MZ-LEL are the refractive index and profile of every zone. The profile can be depicted as the width of the mesa zone, while the lengths and tilt angles of subsequent zones can be labeled as $2L_1$, $L_2$, $L_3$… and $\theta_2$, $\theta_3$…, respectively, as shown in Fig. 4-1(a). A transmission cone, defined as a cone where all the rays are aimed at the vertex of the cone with the incident angles smaller than the critical angle $\theta_0$, is a function of $L_1$, $L_2$, $\theta_2$, $\theta_3$ …and $\theta_0$. Ideally, the transmission cone should cover the whole luminous area, as shown in Fig. 4-1(b). In addition, according to geometric optics, the TIR can be overcome when the profile parameters satisfy the following equations:

$$H \geq \frac{w + L_1}{\tan\theta_0} \quad , \tag{4-1}$$

$$\theta_n \leq \tan^{-1}\left(\frac{H - \sum_{i=1}^{n-1} L_i \sin\theta_i}{w - \sum_{i=1}^{n-1} L_i \cos\theta_i}\right) + \theta_0 - \frac{\pi}{2} \, , \tag{4-2}$$

and

$$L_n \le \frac{H - w\tan\left(\frac{\pi}{2} - \theta_0 - \theta_n\right) - \sum_{i=1}^{n-1}\left[L_i \sin\theta_i - L_i \cos\theta_i \tan\left(\frac{\pi}{2} - \theta_0 - \theta_n\right)\right]}{\sin\theta_n + \cos\theta_n \tan\left(\frac{\pi}{2} - \theta_0 - \theta_n\right)}. \tag{4-3}$$

Here, $H$ and $w$ are the height of MZ-LEL and half the width of the luminous area, respectively; while $\theta_1$ is the tilt angle of mesa zone and equivalent to zero. Thus, the profile of MZ-LEL can be derived and then superimposed on one OLED pixel, as shown in Fig. 4-1(c).

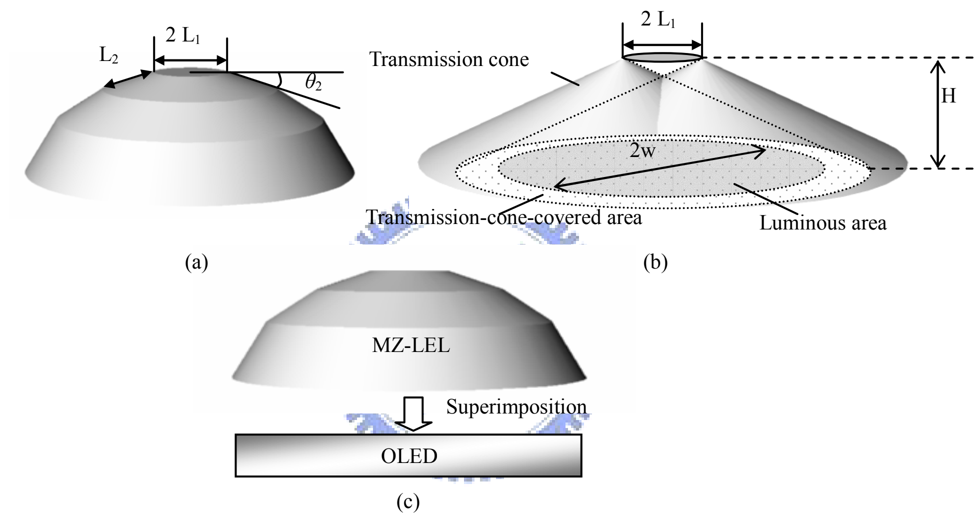


Fig. 4-1 Design of MZ-LEL: (a) profile of MZ-LEL, (b) illustration of the transmission cone of the mesa zone and (c) superimposition of the MZ-LEL on an OLED pixel.

## 4.2 Modeling

### *4.2.1 Fresnel's equation considered*

Earlier studies usually analyzed the LEL on an OLED by ray tracing and assuming that the rays could totally pass through the interface when the incident angles were less than the critical angle. However, the experimental results did not sufficiently agree with the simulated ones.[3] Therefore, in order to have the ray-tracing model approximate the practical situation within an acceptable level of tolerance, the Fresnel's equation, which describes the coefficients of reflection and transmission as light interacting with a smooth boundary, shall be applied to the model. Thus, in contrast to earlier pure-ray-tracing models, we propose a model which also incorporates the calculation of the Fresnel's equation. Herein, ASAP$^{TM}$ 2005 was used to calculate the Fresnel's equation for the proposed model.

To evaluate the design of MZ-LEL, two factors, efficiency and gain, are defined as follows:

$$Efficiency = \frac{Flux\ onto\ the\ detector}{Flux\ from\ the\ illuminative\ area} , \qquad (4\text{-}4)$$

and

$$Gain = \frac{Efficiency_{\ OLED\ with\ LEL}}{Efficiency_{\ referential}} , \qquad (4\text{-}5)$$

where the referential OLED is a conventional OLED without any LEL. Due to the same luminous area of both the LEL-attached OLED and the referential OLED, the gain factor derived by measuring the fluxes on the detector is the main evaluative factor in the following experiments.

### *4.2.2 Preliminary verification using a single-pixel OLED*

In order to verify the model incorporating the calculation of the Fresnel's equation, a single-pixel MZ-LEL with polymethylmethacrylate (PMMA) was first designed and investigated. This MZ-LEL consisted of four zones, and the size of luminous area of OLED was 1.6 x 1.6mm$^2$. The radiating direction of light was assumed to be a random Lambertian distribution. By calculating the Fresnel's equation and the fluxes on the detector, the efficiency of the OLED with the MZ-LEL and that of the OLED with a flat glass were derived as 28.0% and 9.1%, respectively; therefore, the simulated gain was 3.1. When the calculation of Fresnel's equation was not included, the efficiency levels of the MZ-LEL-attached and referential OLEDs became 22.5% and 8.9%, respectively, yielding a gain of 2.5. The actual MZ-LEL, as shown in Fig. 4-2, was fabricated by a diamond turning machine. The measured gain factor was 2.9, which is close to that of the model incorporating the Fresnel's equation.

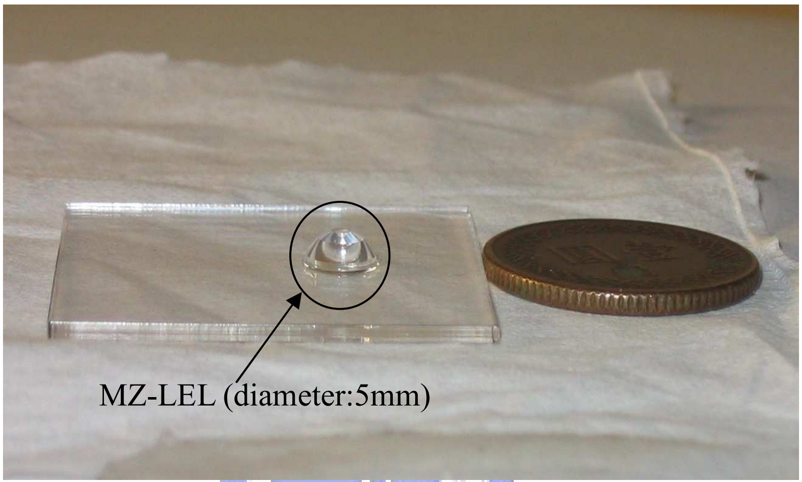


Fig. 4-2 Photo of the MZ-LEL.

### *4.2.3 Examination of earlier research*

An examination was then performed by applying the model with the Fresnel's equation incorporated into the reported micro-lens array LEL.[3] All the dimensions and material parameters were consistent with the published data. Since the dimensions of the top stratum were not provided, they were assumed to be 40 x 40 $mm^2$. The result showed that the referential OLED without LEL yielded an efficiency of 9.8%: close to the experimental datum of 9.5%. Similarly, for the OLED attached with their micro-lens array LEL, again because the size of LEL was not available and because the simulation size of 40 x 40 $mm^2$ requires time-consuming computations, the LEL size was assumed to be a variable and identical to that of the top stratum of OLED.

The simulation results are plotted as the dots in Fig. 4-3. The fitted curve in Fig. 4-3 infers that if the size of the LEL is 40 x 40 $mm^2$, an efficiency of 14.4% is expected; which is close to their measured result of 14.5%.

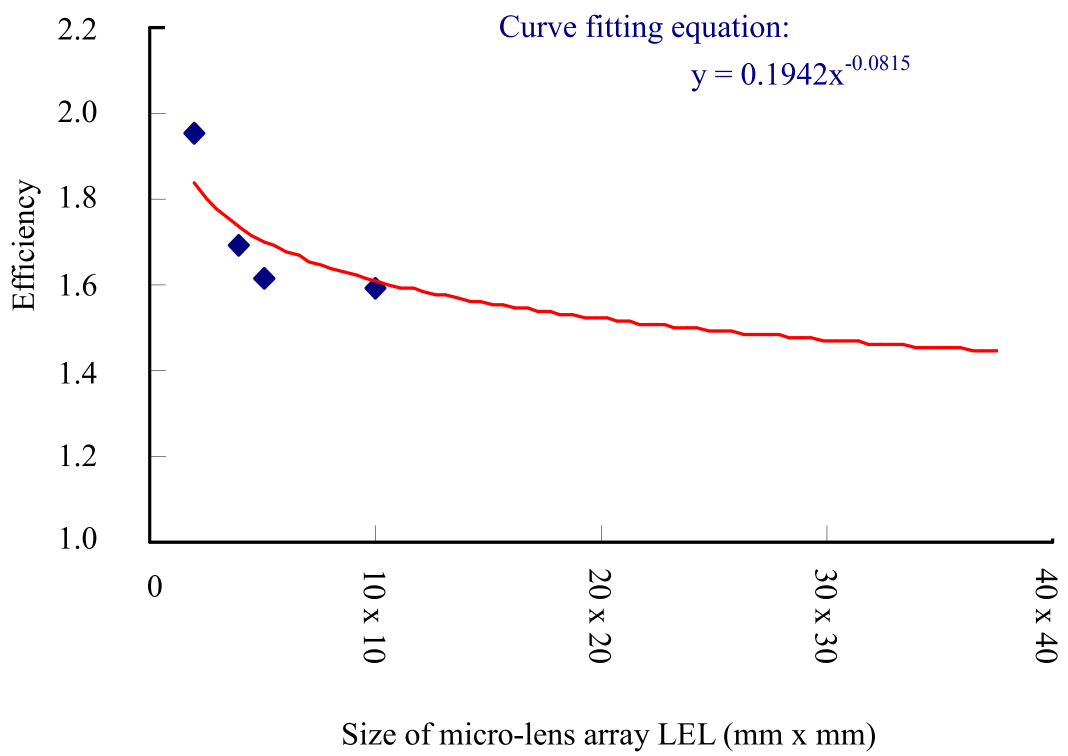


Fig. 4-3 Some simulations of an OLED with an LEL based on an earlier study. The simulation was performed by ray tracing and taking the Fresnel's equation into account.

Brief comparisons of models with and without the Fresnel's equation are listed in Table 4.1, where *G*s and *G*m denote simulated and measured gain factors, respectively. According to the gain deviation factor, defined as (*G*s-*G*m)/*G*s in Table 4.1, modeling the OLED display with the Fresnel's equation included in the computations can bring about an acceptable level of agreement with the experimental results.

Table 4.1 Comparison of different structures with and without the Fresnel's equation

| Examination | Structure | Simulation** | | | | Experiment** | | | Deviation |
|---|---|---|---|---|---|---|---|---|---|
| | | Algorithm | $Eff._R$ (%) | $Eff._L$ (%) | Gs* | $Eff._R$ (%) | $Eff._L$ (%) | Gm* | $\frac{\lvert Gs-Gm \rvert}{Gm}$ (%) |
| Prior literature[3] | Micro-lens array | Ray tracing | -- | -- | 2.3 | 9.5 | 14.5 | 1.5 | 50 |
| Proposed model for prior literature | Micro-lens array | Ray tracing with FEC* | 9.8 | 14.4 | 1.5 | 9.5 | 14.5 | 1.5 | 4 |
| Conventional model for MZ-LEL | Single pixel, multi-zoned | Ray tracing w/o FEC* | 8.9 | 22.7 | 2.5 | -- | -- | 2.9 | 13 |
| Proposed model for MZ-LEL | Single pixel & multi-zoned | Ray tracing with FEC* | 9.1 | 28.0 | 3.1 | -- | -- | 2.9 | 6 |

*Gs, Gm, and FEC denote simulated gain, measured gain, and the Fresnel's equation computed, respectively.
** $Eff_R$ and $Eff_L$ denote the efficiencies of the referential OLED and the LEL-attached OLED, respectively.

## 4.3 Arrayed LEL with multi-zoned shape for OLED panel

### *4.3.1 Model of light source*

Once the optical model of an OLED pixel with an attached LEL has been approved, it is then necessary to focus on its implementation and application to a panel. A typical OLED panel consists of bottom glass and upper substrates, electrodes and organic layers, as illustrated in Fig. 4-4. To establish a model for the arrayed pixels in an OLED panel, it was assumed that the electrodes and organic layers compose one light source layer in the shape of arrayed cuboids, as shown in Fig. 4-4. In addition to the refractive index of every layer, the size of every OLED pixel, the pixel pitch and the dimensions of insulators are also taken into account.

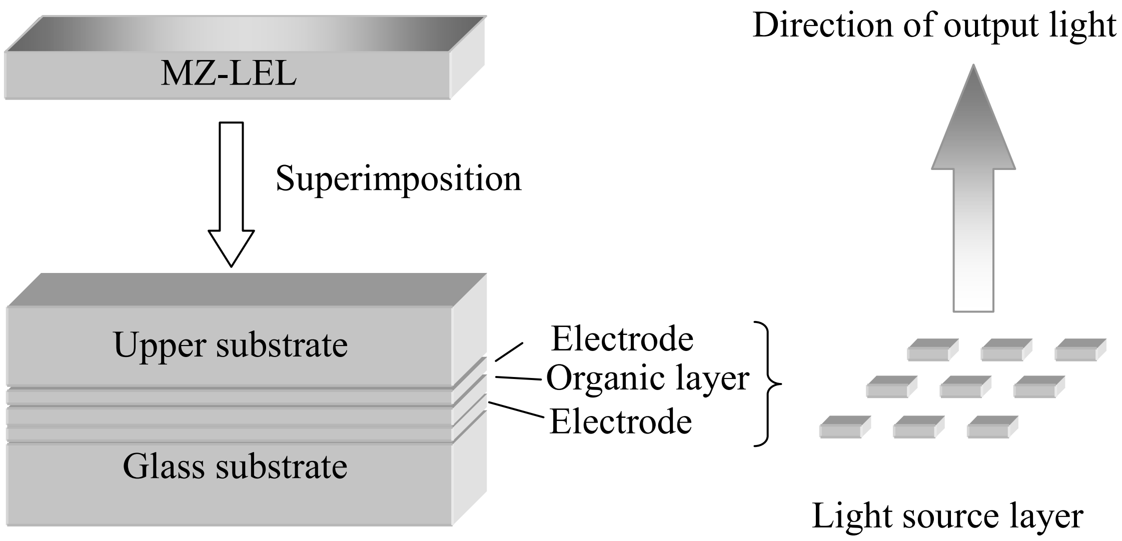


Fig. 4-4 Optical model of OLED panel.

### *4.3.2 Experiment and analysis*

A 70 x 70-pixel arrayed LEL (ALEL) with the multi-zoned shape, or called arrayed MZ-LEL, was then designed for an OLED panel to investigate the model. Each ALEL pixel corresponded to one OLED pixel and possessed two zones, as illustrated in Fig. 4-5. To satisfy fabrication requirements, the tilt angle and the total height of the inclined zone were designed as 54.7° and 187 μm, respectively. Finally, the simulated gain factor was derived as 1.32.

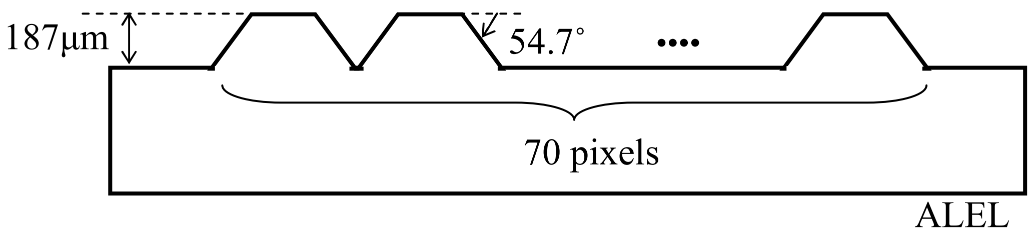


Fig. 4-5 Side-view of ALEL.

The sample was produced using micro-fabrication techniques. First, a mask layer of $SiN_x$ (500 nm thick) was deposited on a silicon wafer using the low pressure chemical vapour deposition process (LPCVD). Next, the processes of photolithography and RIE etching of $SiN_x$ were used to define the pixel size. This step was followed by wet etching of the silicon. The resultant wafer was used as the mold. Using the imprint technique, polydimethylsiloxane (PDMS) copied the profile of the mold. After de-molding, an ALEL made with PDMS was obtained. The fabricated ALEL was then laminated on an OLED panel to examine its optical function, as shown in Fig. 4-6. The measured gain factor was 1.19. The lower gain, compared with the simulated value, was investigated and found to be the result of the Fresnel reflection that occurred at the air gap between the ALEL and the OLED panel.

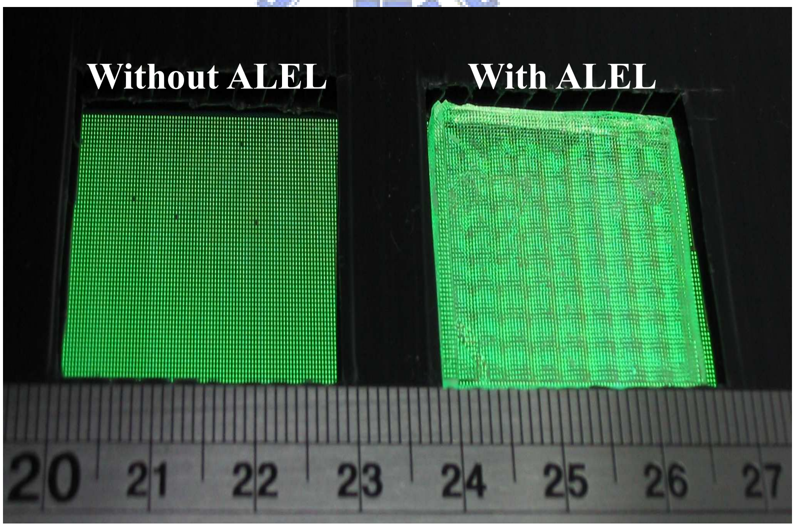


Fig. 4-6 Photo of an OLED panel with and without ALEL.

To eliminate this air gap, a kind of transparent index-matching glue was used to bond the ALEL and the OLED panel together. After setting the thickness of the glue at 5 μm, our analysis showed that the refractive index of glue should range from 1.3 to 1.7 in order to limit the decrease in efficiency to less than 1%, as plotted in Fig. 4-7.

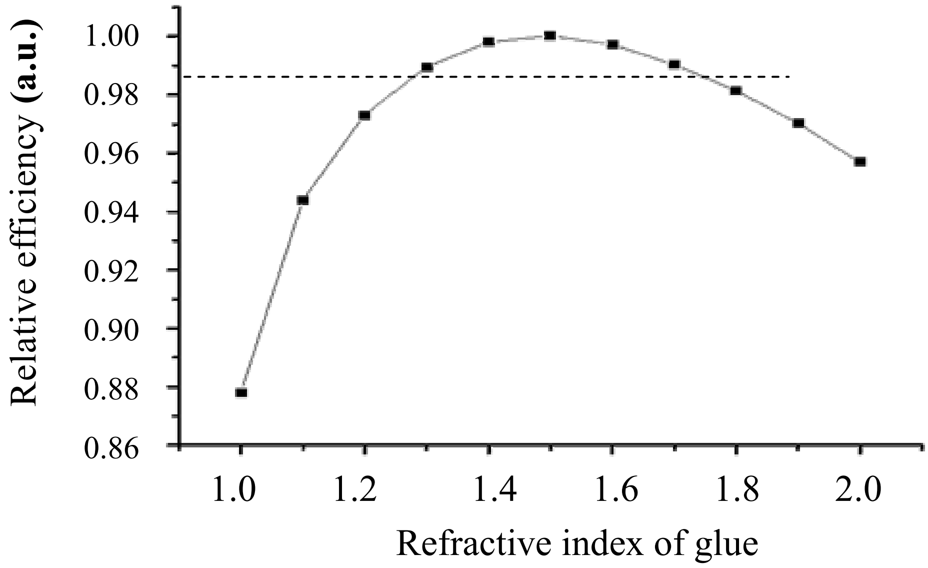


Fig. 4-7 Effect of the refractive index of glue.

Besides the refractive index, the index-matching glue must also have the following qualities: a high transmittance for visible lights, a good adhesion to both the ALEL and the top stratum of OLED panel, a strong resistance to any deformation resulting from the solidification of the glue. Because thermal glue often causes deformation of ALEL, the glue cured by UV light is preferable to the thermal one. In short, the UV glue[5] was found to satisfy these requirements. As a result, the experimental gain factor was found to be 1.28. That is, the simulated gain is consistent with the experimental result within a 4% deviation.

## 4.4 Discussions

In accordance with the above analyses, it can be seen that the optical model for an OLED display incorporating the Fresnel's equation improves the modeling accuracy. The reason can be interpreted as follows. From the results herein, it has been shown that the Fresnel reflection at an interface markedly affects the flux prediction of an OLED display. Thus, the conventional ray tracing, neglecting the wave properties of light such as the attenuation of transmission and reflection at a boundary, leads to an unrepresentive model. Since the transmission and the reflection at an interface are governed by the Fresnel's equation[6] that are angular- and polarization-dependent, it is necessary to incorporate such equations into a ray-tracing model. This can be realized by the developed method of polarization ray tracing.[7] As a result, when a ray-tracing model combines the Fresnel's equation, the characteristics at an interface of an OLED display, such as the refractive indexes of materials, the flux apportionment for reflected and transmitted rays and their directions, can be modeled.

With the established model, the proposed ALEL on an OLED was further analyzed. The result showed that if one of the crucial dimensions, $2(L_1+ L_2\cos\theta_2)$, were to be fabricated to within a ±10 μm window, equivalent to a ±3% profile deviation, then the gain would deviate by no more than 6% from what is expected. Experimentally, the profile deviation of ALEL was found to be less than 7.8 μm when measured using an optical microscope. As mentioned above, the gain deviation was within 4%; thus, the actual result was consistent with what was predicted. In other words, the currently available processes can provide an adequate fabrication window for ALEL so that the experimental results can be consistent with the model ones.

Compared with the gain factor of approximately 1.5 in earlier studies,[3],[4] the ALEL exhibited a lower value of 1.28. The main reason for this lies in the profile of the light source. Unlike a disk-like light source in earlier studies,[3],[4] the light source of the OLED panel herein is arranged as arrayed pixels with insulators between them. Because the size and spacing of the OLED pixels are fixed, the arrangement and space for ALEL pixels are restricted. Consequently, the improvement in the light efficiency is limited and can not equal those of previous studies. [3],[4] To further improve the out-coupling light efficiency of an ALEL-attached OLED panel, both the spacing and the size of OLED pixels and the profile of ALEL would require further optimization and development. Such development would result in an increase in the flexibility of the design, as well as a gain factor of more than 1.5 in light efficiency. Recently, our optimized ALEL has improved the light efficiency of an OLED panel with the fixed pixel size by a gain factor of 2.03 experimentally. [8]

Although the demonstrated ALEL was fabricated with only two zones via standard semiconductor processes, the multi-zoned profile can be fabricated by other available processes, such as excimer laser machining,[9] diamond machining and imprinting. By means of such processes to increase the number of zones, along with the well-organized OLED and ALEL pixels, the level of light efficiency is supposedly further enhanced.

## 4.5 Summary

By means of existing fabrication processes, it has been demonstrated that a precise profile of multi-zoned light-enhancing layer (MZ-LEL) can be produced. Furthermore, by incorporating the Fresnel's equation into the simulation, modeling accuracy has been ensured. The investigation of a single-pixel MZ-LEL has shown that the gain factor in light efficiency attained using this model deviates from the measured value by less than 6%. In addition, when this model was applied to earlier study, it has exhibited an improvement in gain deviation from 50% to 4%. Finally, an OLED panel of 70 x 70 pixels with the arrayed MZ-LEL (ALEL) yielded a gain of 1.28, a result which has shown that the proposed model can reach a gain deviation of less than 4%. To sum up, we have demonstrated that the optical model of the OLED and the fabrication process of a light-enhancing layer (LEL) with sufficient accuracy results in a more effective design of the LEL, which in turn increases the light efficiency of an OLED display; as a result, energy is saved and the life-span of an OLED can be extended.

## 4.6 Reference


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