Chapter 4

Simulated Results and Discussions

4.1. Introduction

According to the principle described in chapter 2, a simulation model was utilized to characterize the features of the micro-lens array structure.

Firstly, the definitions of the light efficiency and enhancement in transmissive mode were given and then the relationship of the light efficiency in reflective mode to radius of micro-lens was analyzed. Besides, a novel directional backlight module was proposed to provide a small divergent angle of light source, and then the capability of micro-lens structure for collecting light can be further enhanced. Based on utilizing the directional backlight as light source, the optimized micro-lens structure was designed.

4.2. Simulation Software

Advanced System Analysis Program (ASAP^{TM}) was used to perform the directional backlight module. In addition, the optical simulator ZEMAX developed by Focus Software, Inc. was used to design the optimized micro-lens structure.

4.3. Analysis of Light Efficiency Enhancement in Transmissive Mode

Micro-lens structure can be classified into circular-type and lenticular-type, as shown in Fig. 4.1. Because the fill factor of lenticular-type lens is larger than that of circular-type lens, lenticular-type can produce higher optical throughput. As a result, in the following design, lenticular-lens was adopted as backlight collective component and optimized to provide highest light efficiency enhancement.

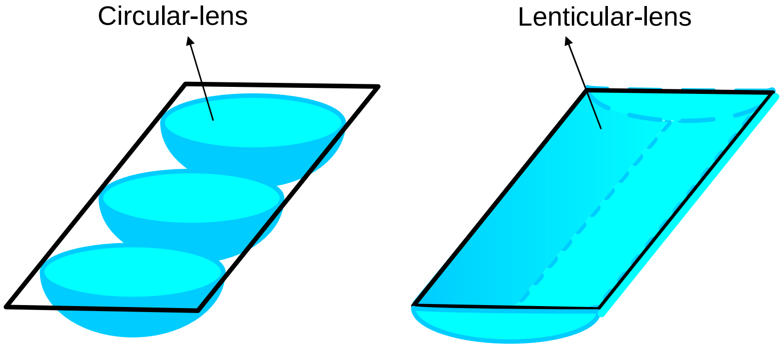


Fig. 4.1. Comparison of fill factors of (a) circular-lens and (b) lenticular-lens

Prior to a discussion of the light efficiency in transmissive mode, several assumptions are given as follows. All of the light entering the micro-lens array can exit from the transmissive region. The width and length of each sub-pixel are 70um and 210um, respectively. The lateral sizes of transmissive and reflective regions of conventional transflective LCD are equal to 35 um. As schematically shown in Fig. 4.2, the diameter of the lenticular-lens is denoted as D, the width and length of sub-pixel are W and L, respectively, and the aperture size of the reflective(R) region is AP. Besides, the light efficiency is assumed to be proportional to area ratio. Therefore, the light efficiency of conventional structure is derived as AP*L divided by W*L, i.e. the light efficiency is 0.5. In addition, the light efficiency of the lenticular-lens structure is defined as D*L divided by W*L. Moreover, the light efficiency enhancement in transmissive mode is determined by the ratio of the light efficiency of micro-lens to conventional structure. According to the definitions mentioned above, it is appear that the light efficiency enhancement in transmissive mode becomes larger when D increases. The calculated results are shown as Fig. 4.3. The light efficiency enhancement in transmissive mode can be increased by a factor of two at D=70um, yet, causing disturbance between two adjacent regions in fabrication process. Thus, in fabrication process, 68um of diameter of lenticular-lens structure was chosen. In this case, the light efficiency enhancement is of 1.94.

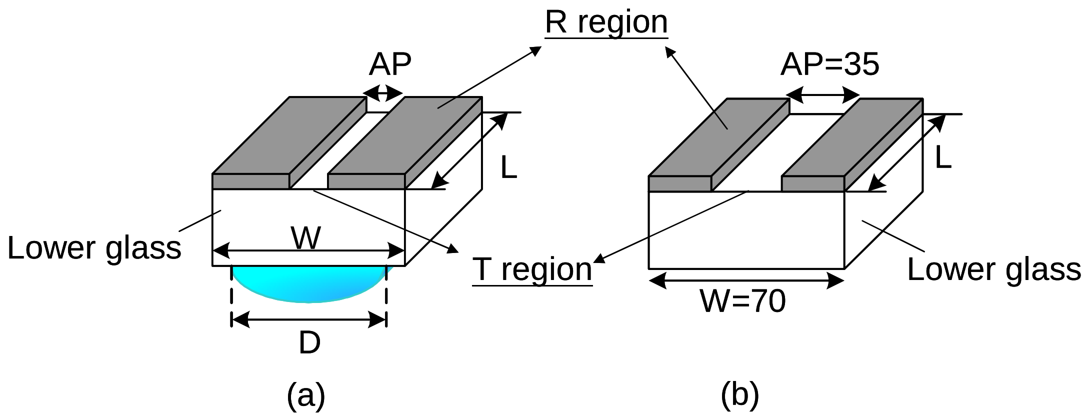


Fig. 4.2. Illustrative figures of the parameters of (a) a lenticular-lens structure and (b) a conventional structure

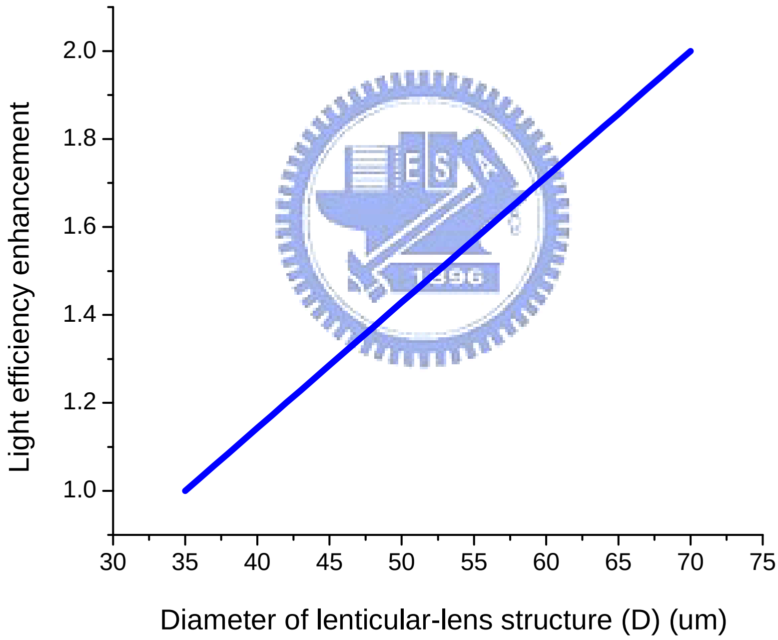


Fig. 4.3. Light efficiency enhancement as a function of diameter of lenticular-lens structure

4.4. Simulation of Light Efficiency Enhancement in Reflective Mode

The amount of reflected light depends on area of reflective region, as illustrated in Fig. 4.2. Thus, the light efficiency in reflective mode also can be defined as the area ratio. Consequently, the light efficiency of both conventional structure and lenticular-lens structure can be derived as (W-AP)*L divided by W*L. According to the assumption about the conventional structure (section 4.3), the light efficiency of the conventional structure is 0.5. Besides, it is obvious that the reflected light efficiency of lenticular-lens structure becomes larger when AP decreases. However, as shown in Fig. 4.4, in order to obtain the highest light efficiency in transmissive mode, the aperture size of the reflective region must be equal or larger than the spot size of collected backlight. Thus, we conclude that the highest light efficiency in reflective and transmissive modes can be obtained when the spot size of collected backlight is as small as possible.

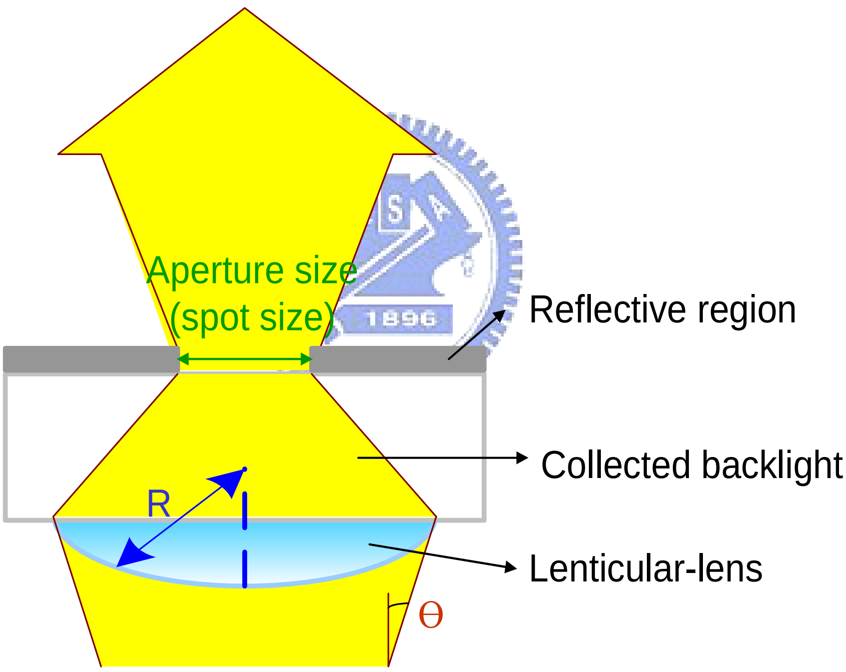


Fig. 4.4. Illustrative diagram of the parameters for obtaining highest light efficiency in transmissive and reflective modes

In order to obtain a minimum spot on the transmissive region, several parameters, such as radius of the lenticular-lens structure and the divergent angle of incident backlight, must be adjusted properly. As illustrated in Fig. 4.4, the radius of the lenticular-lens structure is defined as R, and the divergent angle of incident backlight is θ. The optical simulator ZEMAS was utilized to evaluate the relationship of spot size of collected backlight on transmissive region to radius (R) of the lenticular-lens structure, while the divergent angle (θ) of incident backlight equals to 10˚, 15˚ and 20˚, respectively, as depicted in Fig. 4.5.

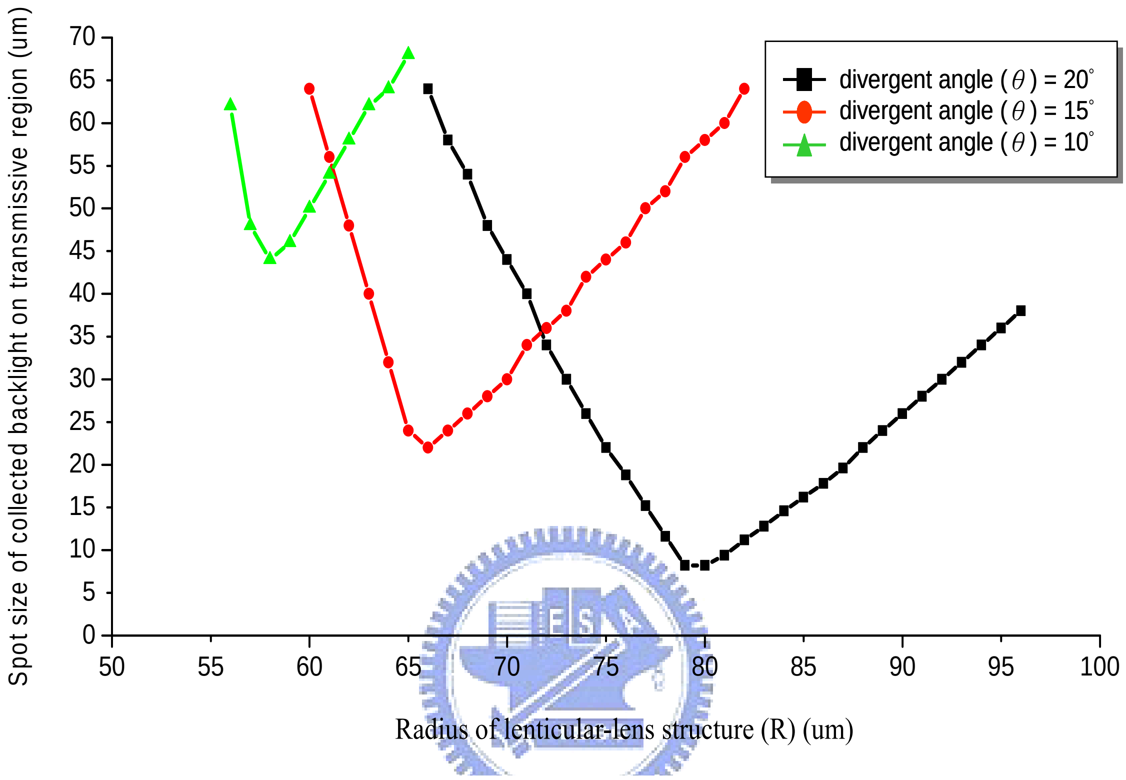


Fig. 4.5. Simulation results of spot size as function of radius of lenticular-lens (R) and divergent angle of backlight (θ)

It is apparent from this figure that smaller divergent angle of backlight module can provide smaller spot size of collected backlight and then decreasing the aperture size of reflective region to obtain higher light efficiency in reflective mode. However, in practical applications, the divergent angle of backlight module is roughly about 40˚~60˚. As a result, if commercial backlight is adopted as light source, the spot size will be larger than the sub-pixel size, thus, resulting in significant improvement of reflected light efficiency can not be obtained. Therefore, a novel directional backlight with divergent angle of 15˚ was proposed in the following section.

4.4.1. Directional Backlight Module

As the simulation result described above, if R was fixed, smaller divergent angle can provide smaller spot on transmissive regions. Thus, a novel directional backlight with divergent angle of 15° was proposed. The principle and simulation of the directional backlight are given in follows.

4.4.1.1. Principle of Directional Backlight

A directional backlight composed of a lower grooved lightguide and upper reversed prism sheet was utilized to redirect the incident light to normal direction, as schematically shown in Fig. 4.6. When the light source was switched on, a larger inclined angle of viewing cone was emitted from the lower grooved lightguide. A total internal reflection occurred at the interface of the upper reversed prism sheet, which was followed by a refraction of the larger inclined angle. Thus, the upper reversed prism sheet redirected the light to a smaller divergent angle. Based on the geometric derivations (Fig. 4.6), the relationship between θ, θ_1, θ_2 and θ_3 can be described by Equations (1), (2) and (3). Substituting θ_1 and θ_2 from Equations (1) and (2), the divergent angle of directional backlight was derived as Equation (4).

$$n \times \sin\theta_1 = \sin[\theta - (\alpha - \beta)] \quad \text{.......(1)}$$

$$\theta_2 = 2\beta - \theta_1 \quad \text{.......(2)}$$

$$\beta - \theta_3 = 90 - \theta_2 \quad \text{.......(3)}$$

$$\theta_3 = 3\beta - 90 - \sin^{-1}[\frac{\sin(\theta - \alpha + \beta)}{n}] \quad \text{.......(4)},$$

where θ is the emitted angle from lower grooved lightguide, θ_1 is the refracted angle at the left side interface of upper reversed prism sheet, θ_2 is the incident angle at the right side interface of upper reversed prism sheet, θ_3 is the divergent angle of directional backlight, β and α depict the half vertex angles of upper reversed prism sheet and lower grooved lightguide, respectively, n is the refractive index of upper reversed prism sheet.

From Equation (4), assuming the vertex angles of lower grooved lightguide and upper reversed prism sheet were 170˚ and 60˚, respectively, the emitted angle (θ) from the lower grooved lightguide was 70˚. The refractive index of the upper reversed prism sheet was set to be 1.49. Consequently, 15˚ of divergent angle (θ_3) of directional backlight can be obtained. It is evident that a directional backlight module with small divergent angle is feasible.

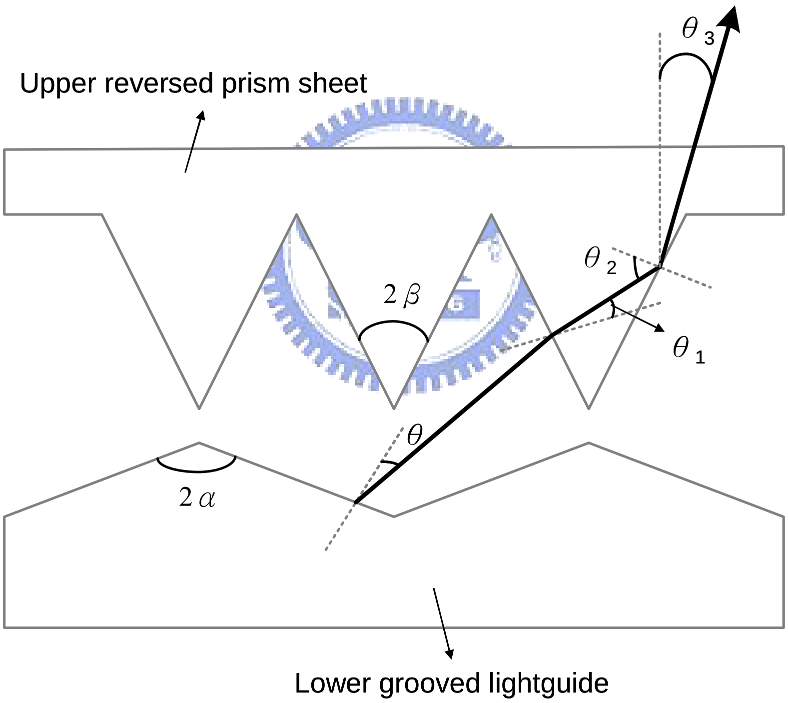
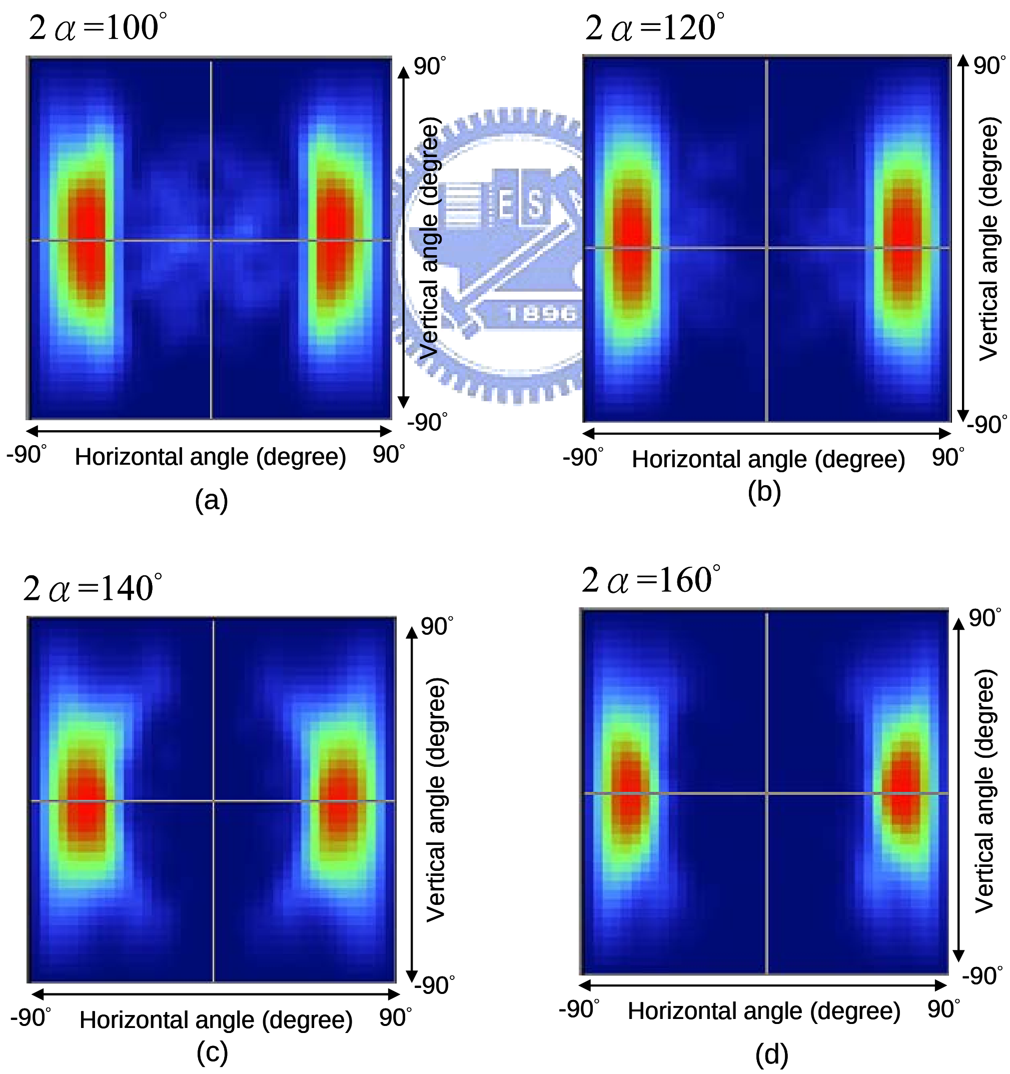


Fig. 4.6. Schematic diagram of directional backlight

4.4.1.2. Optimization of Directional Backlight

In order to obtain more precisely specifications of directional backlight, an optical simulator ASAP was utilized to optimize the geometric structures of grooved lightguide and reversed prism sheet. At first, the emitted angular distribution from lower grooved lightguide was simulated by varying 2α from 100˚ to 170˚ at 5˚

intervals. Some of typical results are listed in Fig. 4.7. Obviously, the viewing cone of emitted light from lower grooved lightguide was not concentrated when 2α increased from 100˚ to 160˚. Thus, it is difficult to make all incident light totally internal reflect at the right side interface of upper reversed prism sheet, and then small divergent angle of backlight module can not be obtained. In contrast, when 2α changed from 160˚ to 170˚, the emitted cone from the lower grooved lightguide was more condensed. Thus, small divergent angle of backlight was easier to realize. In addition, due to the limitation in fabrication process, 165˚ of vertex angle of lower grooved lightguide was adopted.



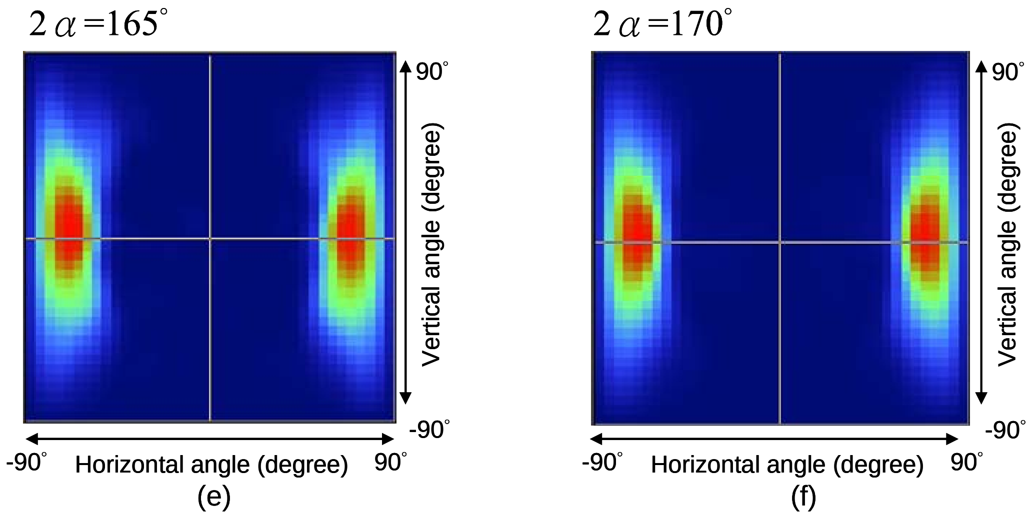


Fig. 4.7. The angular distribution of emitted light from lower grooved lightguide when 2α = (a) 100˚, (b) 120˚, (c) 140˚, (d) 160˚, (e) 165˚ and (f) 170˚.

In the following, the vertex angle of lower grooved lightguide was fixed as 160˚, the divergent angle of whole directional backlight was simulated when 2β changed from 20˚ to 80˚ at 5˚ intervals. Fig. 4.8 illustrated some of simulation results. It is apparent that the tendency of divergent angle of backlight changed from two peaks to one peak when 2β varied from 20˚ to 60˚. In addition, as 2β increased larger than 70˚, the divergent angle of backlight became two peaks again. Therefore, only 2β varied within the range from 60˚ to 70˚, a backlight with small divergent angle can be obtained. However, comparing of Figs. 4.8(d), (e) and (f), 68˚ of vertex angle of upper reversed prism sheet can provide the most collimated angular distribution. In the following design, a directional backlight composed of a 165˚ vertex angle of lower grooved lightguide and a 68˚ vertex angle of upper reversed prism sheet was utilized as light source to illuminate the lenticular-lens array.

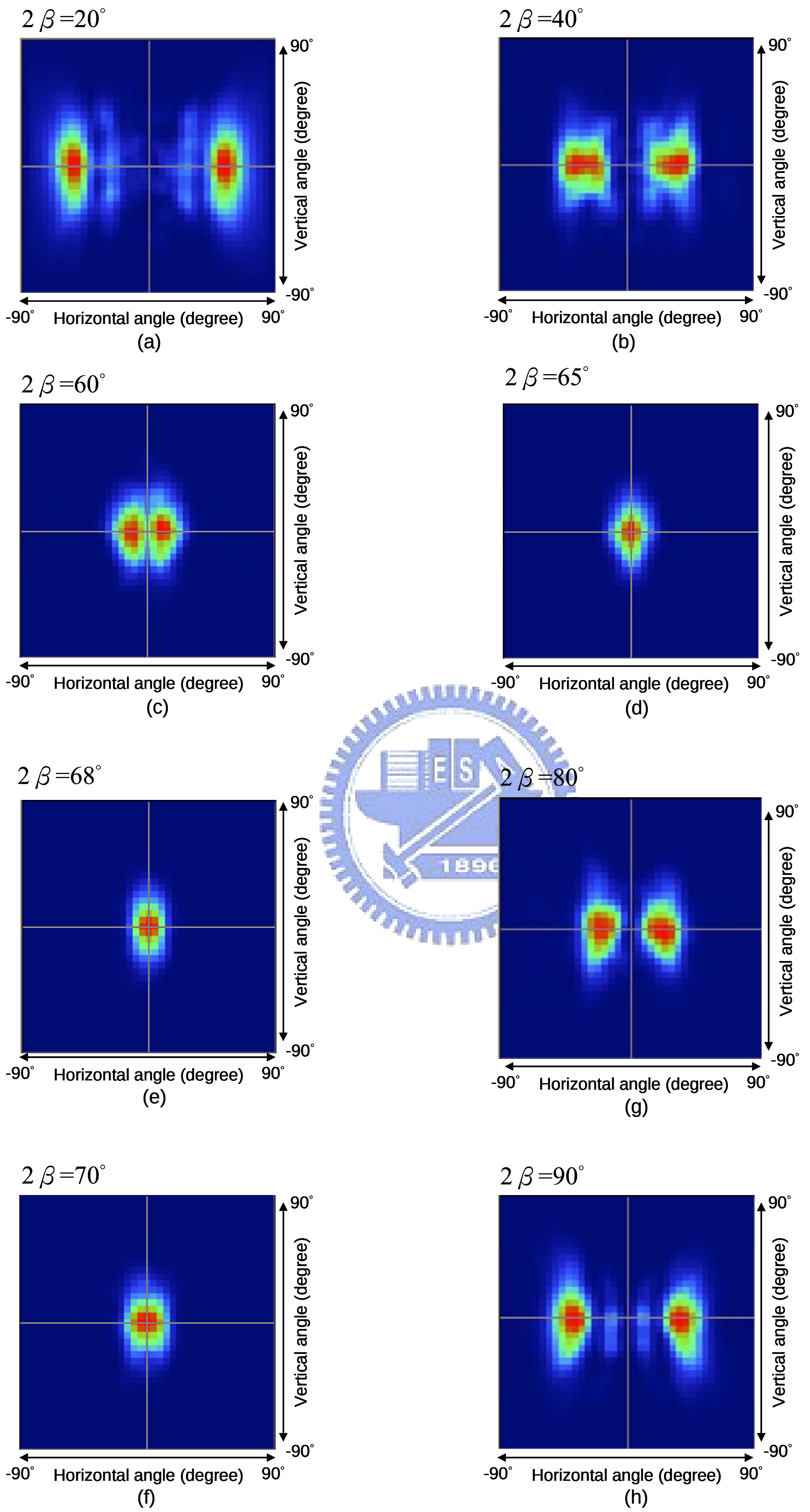


Fig. 4.8. The divergent angle of backlight module when 2β = (a) 20°, (b) 40°, (c) 60°, (d) 65°, (e) 68°, (f) 70°, (g) 80° and (h) 90°, respectively.

4.4.2. Optimization of Lenticular-lens Structure

According to the definitions mentioned above, the light efficiency enhancement in reflective mode is defined as the ratio of reflected light efficiency of the lenticular-lens structure to the conventional structure, i.e. the light efficiency enhancement in reflective mode is (W-AP)/W/0.5, where W is the width of sub-pixel and AP is the aperture size of the reflective region. Based on adopting 15° of divergent angle (θ) of directional backlight as light source, Fig. 4.9 depicted the relationship of light efficiency enhancement in reflective mode to radius of the lenticular-lens structure (R). It is apparent that the light efficiency in reflective mode can be increased by a factor of more than one, when the radius of lenticular-lens structure within the range from 64um to 71um. Moreover, the highest light efficiency enhancement is 1.37 when the radius of lenticular-lens structure equals 66um and the aperture size of reflective region equals 22um (Fig. 4.5). Thus, we choose the lenticular-lens structure with specifications of R=66 um, AP=22 um and D= 68 um for the applications.

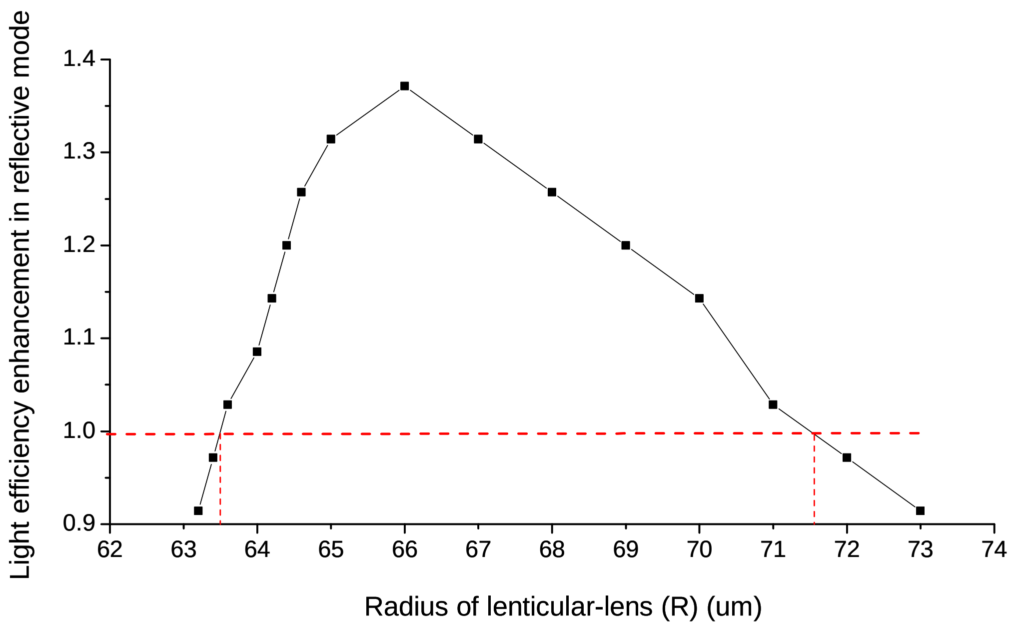


Fig. 4.9. Illustration of the relationship between the light efficiency enhancement in reflective mode to and radius of lenticular-lens structure

4.5. Mask Design

Due to the limitations of lithography and lift-off fabrication processes, the shape of reflective regions was reorganized, as shown in Fig. 4.10. Although the light efficiency enhancement in reflective mode decreases from 1.37 to 1.23, the light efficiency in transmissive mode still can be increased by a factor of 1.94. In the mask design, the shadow regions were used to form transmissive regions, as schematically shown in Fig. 4.11.

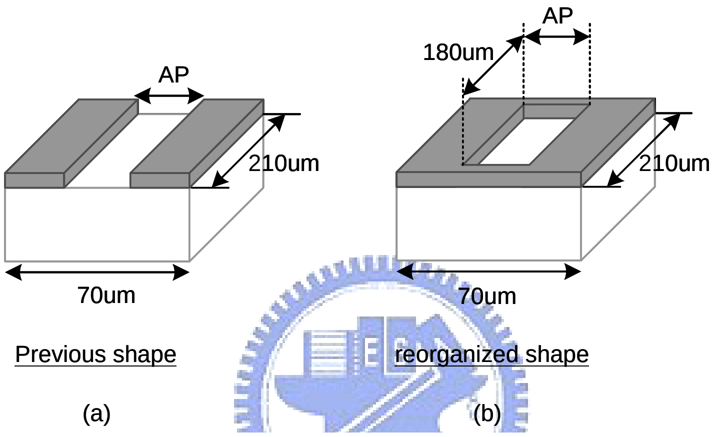


Fig. 4.10. Illustrated diagrams of (a) previous shape of reflective region and (b) Reorganized shape of reflective region

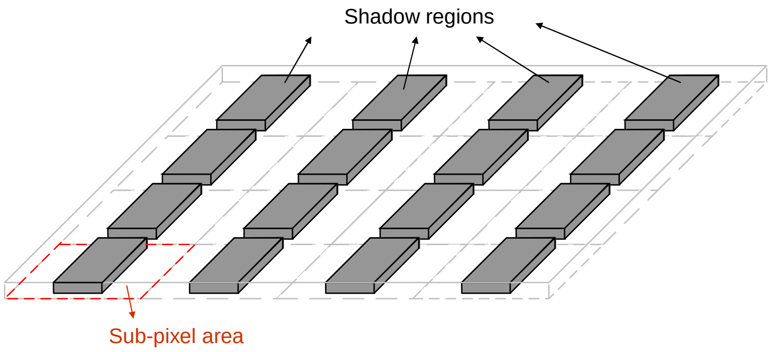


Fig. 4.11. Illustrated diagram of shadow regions on mask

4.6 Summary

We have designed and optimized the lenticular-lens array structure. It is apparent from the mentioned analyses that the structure of lenticular-lens can provide better light efficiency in transmissive and reflective modes compared to conventional transflective LCDs. Moreover, to further enhance the capability of lenticular-lens structure for collecting light, a novel directional backlight with divergent angle of 15° was proposed. As a result, a transflective LCD composed of a lenticular-lens structure and a directional backlight can increase the light efficiency in reflective and transmissive modes by a factor of 1.3 and 1.9, respectively. Finally, in following fabrications, a reorganized shape of reflective region was adopted to be compatible to lithography and lift-off processes.