Chapter 6

Micro-tube Array on Transflective Displays for Backlight Efficiency Increase

The light control film[72], [73], [74] and image-enhanced reflector[86], [92] can respectively improve the reflective and transmissive image quality of a transflective LCD. However, the backlight utilization efficiency of a transflective LCD is quite low due to the blocking of reflective region. Hence, a novel transflective liquid crystal display (LCD) with a microtube array structure to make the most effective use of backlight was demonstrated. By redefining the area ratio of transmissive and reflective regions, high light efficiency in both transmissive and reflective subpixels can be attained. Based on the principle of light collection, a simulation model was established to characterize the features and optimize the microtube array structure. Furthermore, a typical TFT-LCD process was utilized to fabricate the optimized structure. A prototype microtube array was fabricated, and the measured enhancement of backlight utilization efficiency can be as high as a factor of 1.81.

6.1 Introduction

Transflective type LCD[99]which realizes both transmissive- and reflective-mode displays in one liquid crystal device has been reported, as shown in Fig. 1. The transflective LCD utilizes a transflective layer, which splits each subpixel into T (transmissive) and R (reflective) portions, to display the image in any ambient. In a bright ambient, the incident ambient light on the T subpixel is absorbed by the lower polarizer and the device works as a reflective display. In a dark ambience, the backlight transmits the T subpixels and the device works as a transmissive display. However, when the backlight system is utilized as the light source, the reflective region blocks most of the backlight for illuminating LCD's, thus greatly reducing the backlight utilization efficiency. Some methods have been reported for improving the backlight utilization efficiency of conventional transflective LCDs, such as prism-on-light-pipe[100]technology and the use of an optical microdeflector [101],which yield 33% and 40% increases of luminance flux, respectively. In order to further enhance the backlight utilization efficiency, a backlight collective component, the microtube array, for transflective LCD technology is proposed.

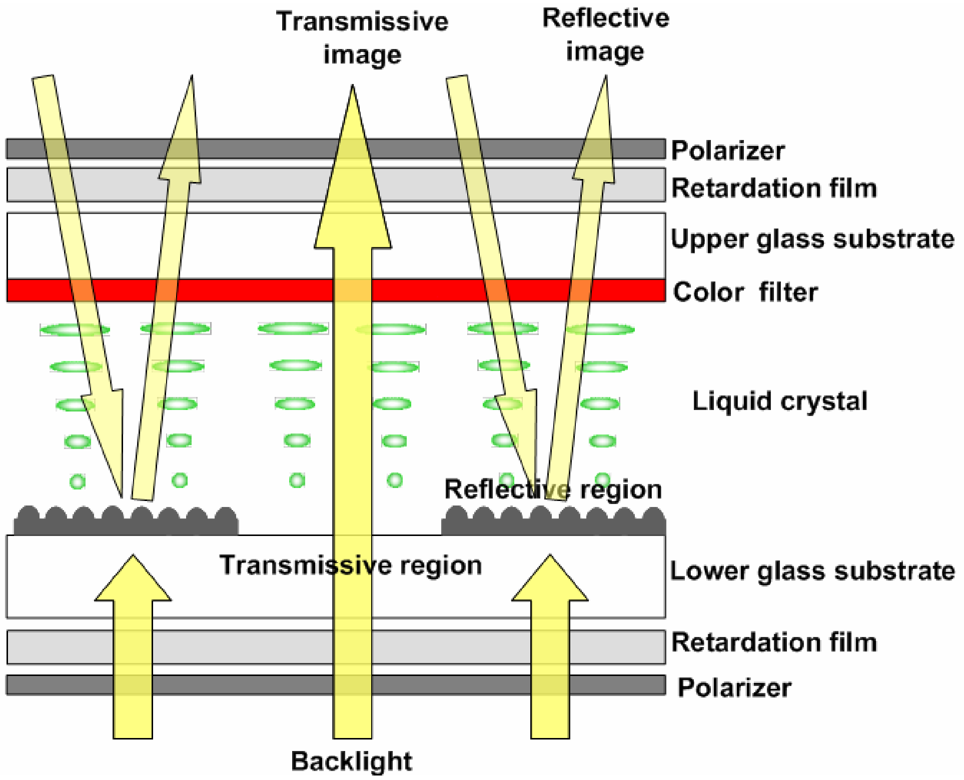


Fig. 6-1. Schematic diagram of a conventional transflective LCD with a backlight system.

6.2 Micro-tube Array (MTA) for backlight efficiency enhancement

We designed different kinds of backlight collective components to enhance the backlight efficiency. First, some structures such as diffractive and refractive components were simulated. However, the results showed only a 30 % increase of luminance flux, which is no higher than that achieved with the prior techniques. Thus, diffractive and refractive structures are unsuitable. Then, a reflective component called a microtube array (MTA) was proposed. The concept of this design is to make use of a microtube structure, which is similar to a funnel in shape, to allow most of the backlight to enter the microtube from a lower aperture, as shown in Fig. 6-2. Due to the nature of the funnel structure, the incident light can be made to exit from the upper aperture so that backlight efficiency can be substantially increased. For a completed structure, the MTA is located between the lower glass substrate and the lower ITO layer in a transflective LCD, as shown in Fig. 6-3, , where a diffuser laminated between the retardation film and upper glass substrate is utilized to render the output of light uniform. In the conventional transflective LCD, only rays passing through the transmissive region can be utilized, thus the utilization efficiency is low. In our novel structure, other than a small fraction of backlight blocked by the areas between each microtube, the rest can mostly pass through the upper apertures of the microtube array, which increases the transmissive light efficiency. Therefore, the increased light efficiency allows the area ratio of the reflective region to the transmissive region to be redefined, which will enable the enhancement of the image quality. As a result, the brightness of the transmitted backlight and reflected ambient light can be optimized so that the image quality can be improved for both indoor and outdoor applications, which is appealing in the mobile display market.

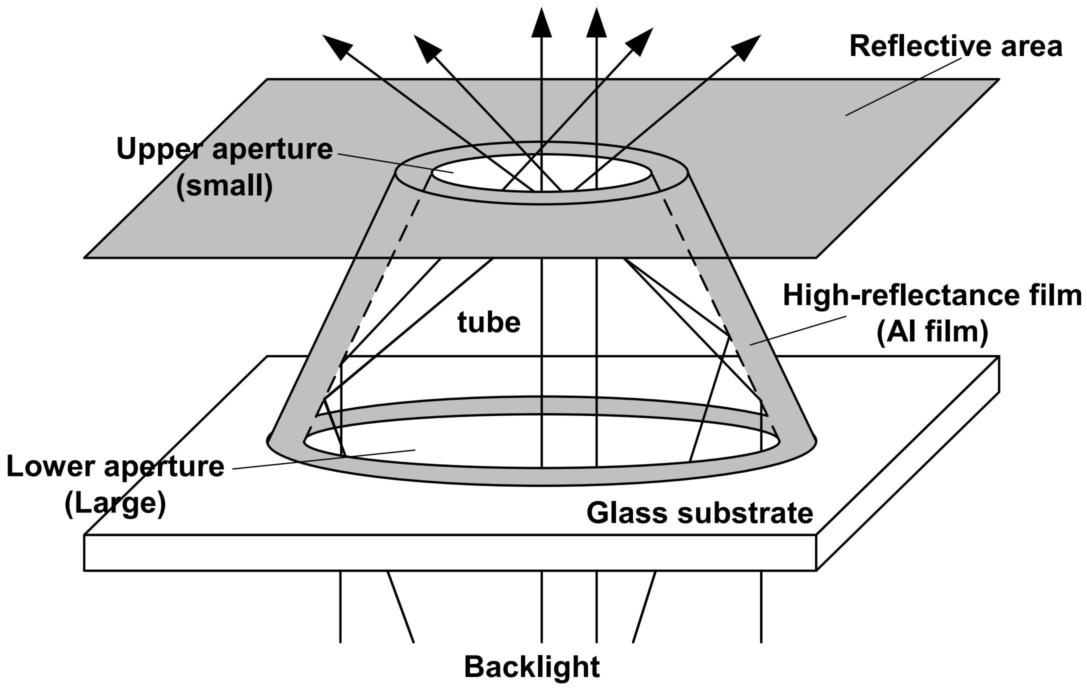


Fig. 6-2. A 3-D schematic of a single microtube structure for backlight collection.

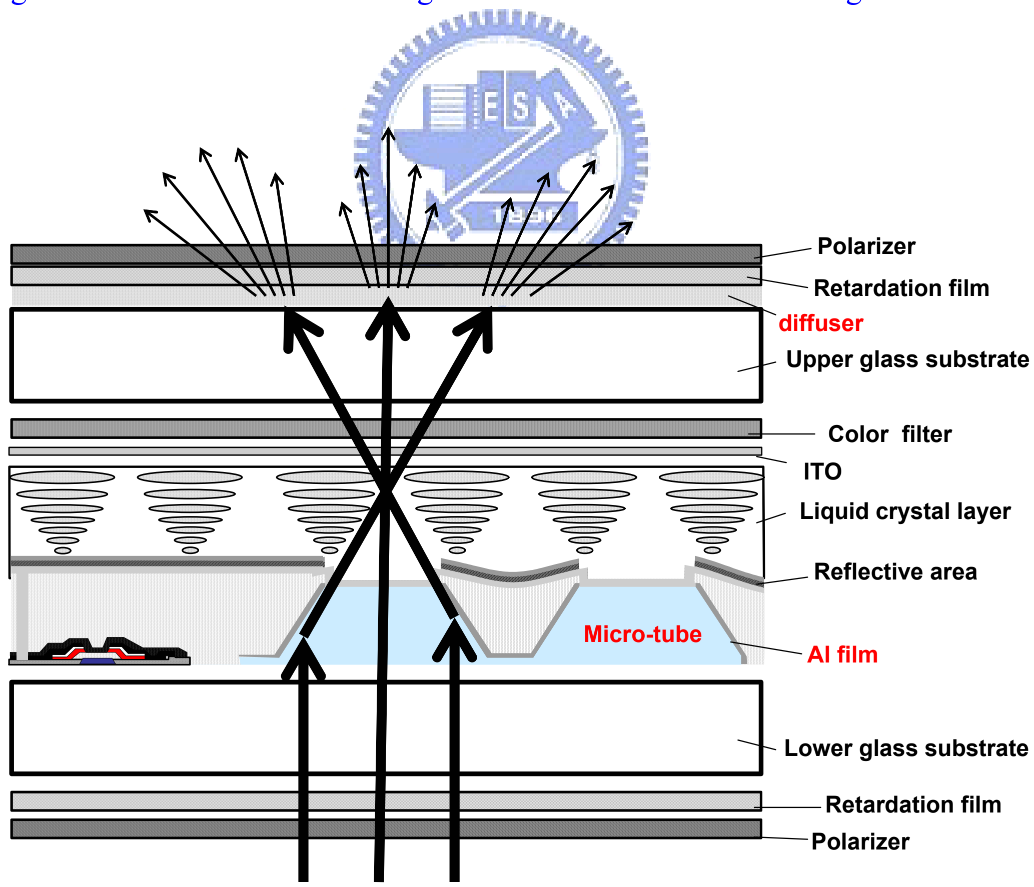


Fig. 6-3. Schematic diagram of a single cell-gap transflective LCD with microtube array.

6.3 Optical design of micro-tube array

In order to analyze the capability of collecting backlight for the MTA, the definitions of backlight utilization efficiency and enhancement shall be given first. The backlight utilization efficiency is defined as the output light flux divided by the original backlight flux. Enhancement is defined as the backlight utilization efficiency of a transflective LCD with the MTA divided by that without the MTA.

6.3.1 Numerical calculation

In order to further optimize the enhancement of the MTA structure, three structure parameters are defined, as shown in Fig. 4(a), where AP is the diameter of the upper aperture, d is the height of a microtube, and θ_{tube} is the tilt angle. In this design, the tilt angle (θ_{tube}) must be steeper than 45°, because once θ_{tube} becomes smaller than 45°, the normal directional incident backlight will be reflected backward, and cannot exit from the upper aperture. Accordingly, if parallel backlight is utilized as the light source, the reflectance of the microtube sidewall is 100%; all the light incident into the lower (larger) apertures can be collected and utilized to display the image. Therefore, the backlight utilization efficiency with and without the MTA can be given as

$$\textit{Backlight utilization efficiency without MTA} = \frac{\pi \cdot \left(\frac{AP}{2}\right)^2}{\textit{Total area}} \qquad (7\text{- }1)$$

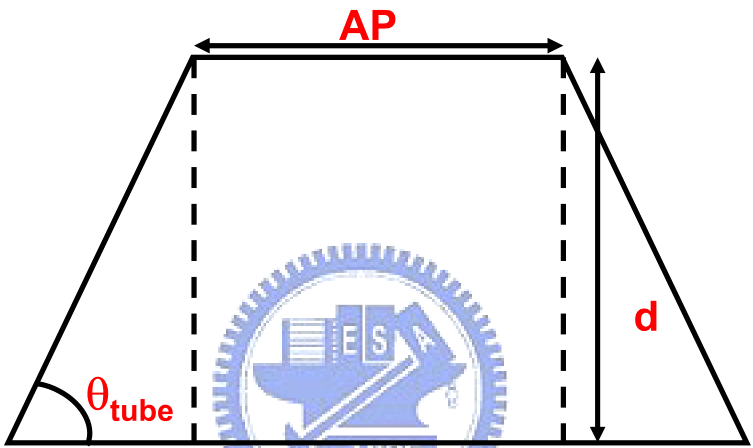
$$\textit{Backlight utilization efficiency with MTA} = \frac{\pi \cdot \left(\frac{AP}{2} + \frac{d}{\tan\theta_{tube}}\right)^2}{\textit{Total area}} \qquad (7\text{- }2)$$

Here total area denotes the entire region of a single tube, as depicted in Fig. 6-4(b). Therefore, the enhancement can be derived as

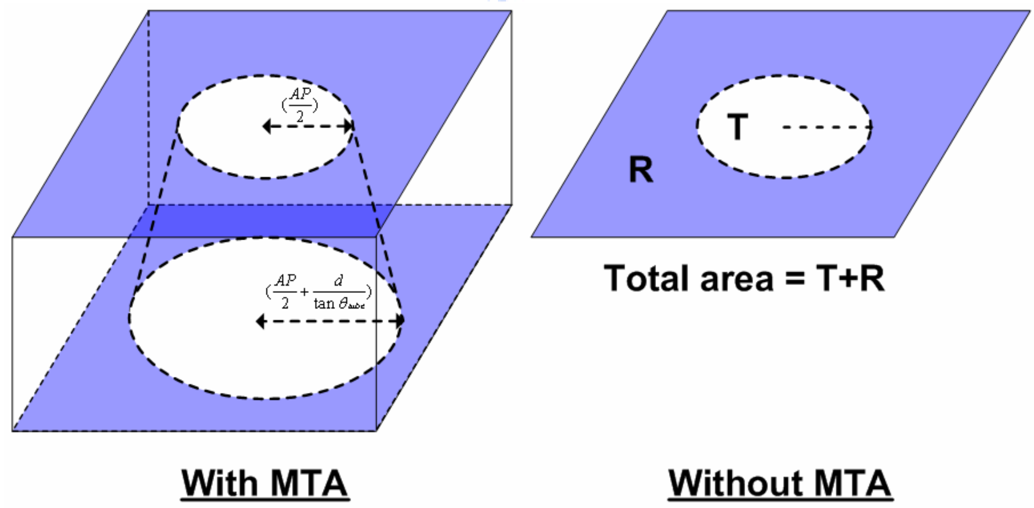
$$Enhancement = \frac{Backlight\ utilization\ efficiency\ with\ MTA}{Backlight\ utilization\ efficiency\ without\ MTA} = \left(1 + \frac{2d}{AP \cdot \tan\theta_{tube}}\right) \quad (7\text{- }3)$$

where $45° < \theta_{tube} < 90°$.

According to Eq.(7- 3), enhancement can be increased by adopting to higher d, smaller AP, and smaller θ_{tube}. However, this numerical result only depends on the condition of parallel backlight. Therefore, an optical simulator, ASAP, is then utilized to further optimize the MTA structure.



(a)



(b)

Fig. 6-4. (a) Three key parameters of microtube array which affect the properties of backlight collection, and (b) schematic of the structure used for numerical calculation.

6.3.2 Optimized simulation

The relationship between enhancement and the three key structure parameters, d, AP, and θ_{tube}, with conventional backlight[102]illumination on a MTA structure was analyzed. First, the upper aperture diameter (AP) was fixed, and the tilt angle (θ_{tube}) was varied from 45° to 65° at 5° intervals. Then the relationship between enhancement and tube height (d) was derived, as presented in Fig. 6-5. It is apparent that enhancement increased gradually as d increased from 2 μm to 4 μm. As a result, a longer structure has a better capability of collecting light.

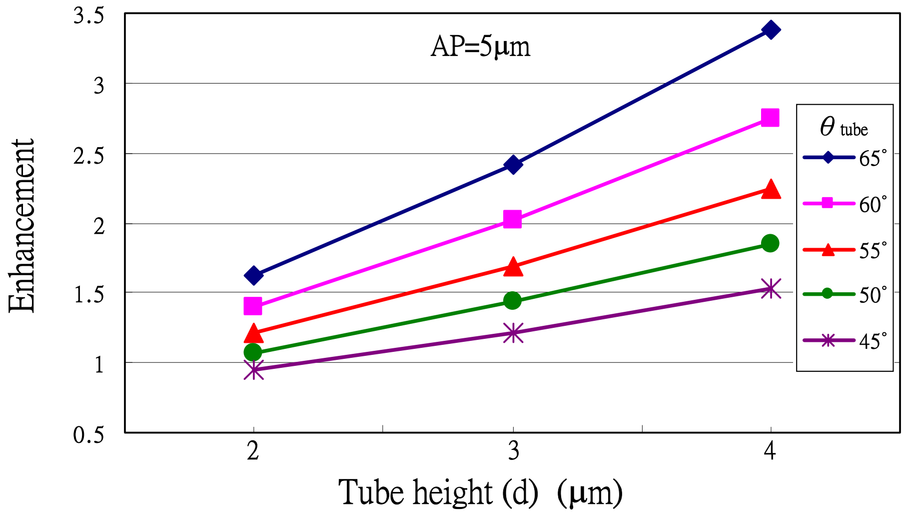


Fig. 6-5. Illustration of the relationship between enhancement and tube height (d) under the condition that upper aperture diameter of a microtube (AP) is fixed.

Moreover, the relationship between the enhancement and AP plotted in Fig. 6-6, under the condition of fixed d, shows that when AP increased from 4 μm to 6 μm, enhancement decreased gradually. Therefore, a smaller aperture can result in greater enhancement. We conclude that the longer the tube and the smaller the upper aperture, the greater the enhancement. However, because of the limitation of the conventional TFT-LCD fabrication process, a structure with d=3 μm and AP=5 μm was chosen for further analyses. Tilt angle (θ_{tube}) also affects the enhancement, as shown in Fig. 6-7, where enhancement increased to a maximum at an angle of 60° and then decreased above 60°. From the simulation results, the MTA with d=3 μm, θ_{tube}=60° and AP=5 μm was chosen as the optimized structure.

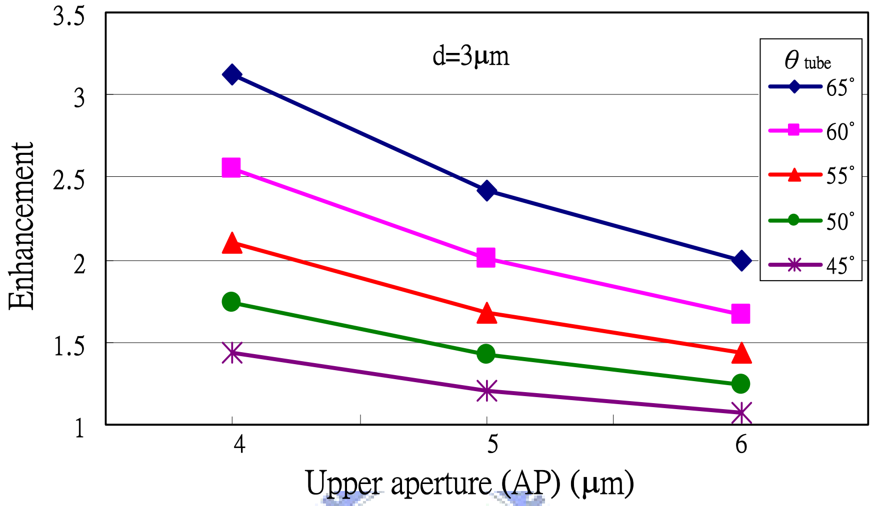


Fig. 6-6. Illustration of the relationship between enhancement and upper aperture (AP) under the condition that tube height (d) is fixed.

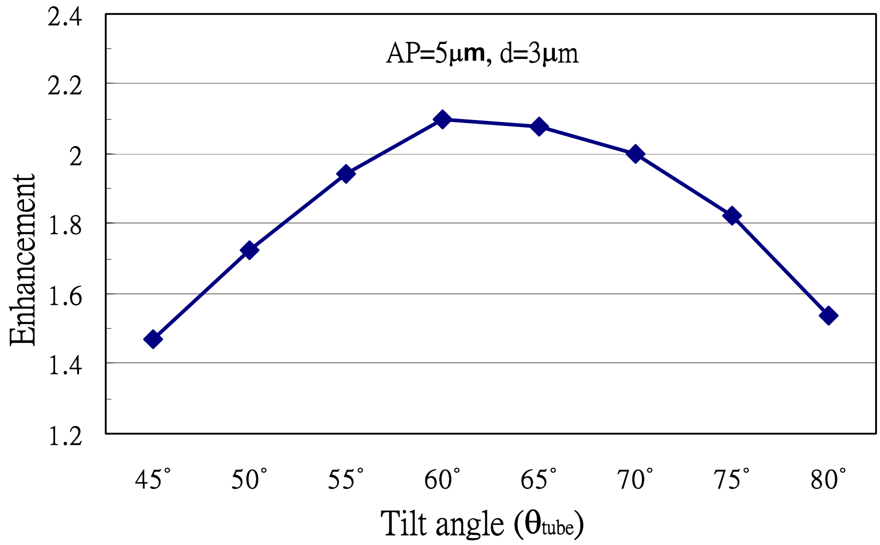


Fig. 6-7. Illustration of the relationship between enhancement and tilt angle (θ_{tube}) under the condition that upper aperture diameter of a microtube (AP) is 5 μm and tube height (d) is 3 μm.

6.4 Experiments

6.4.1 Fabrication of micro-tube array

A prototype of the MTA was fabricated using a typical TFT-LCD process. The detailed fabrication processes are listed below and the flowchart is shown in Fig. 6-8.

(a) A high-transparency organic film was first coated onto a glass substrate. Through the exposure and development of the 1st mask, a preliminary structure of the MTA was formed. Herein, the exposure time of the 1st mask plays a leading role in tube height (d), and the aperture diameter of the 1st mask determines that of the upper aperture (AP)

(b) After modifying the exposure time and aperture diameter of the 1st mask, the thermal reflow process was used to melt the preliminary MTA structure to adjust its tilt angle (θ_{tube}). By careful control of the temperature-increase curve of the oven, the designed tilt angle can be easily achieved.

(c) Aluminum (Al) film and positive photoresist (PR) were then sequentially coated onto the surface of the MTA. The 2nd mask, which has the opposite pattern to that of the 1st mask, was utilized to release the photoresist above the upper apertures.

(d) Finally, by the wet etching process, the remaining PR and the aluminum film above the upper apertures were removed. Consequently, a MTA structure was fabricated.

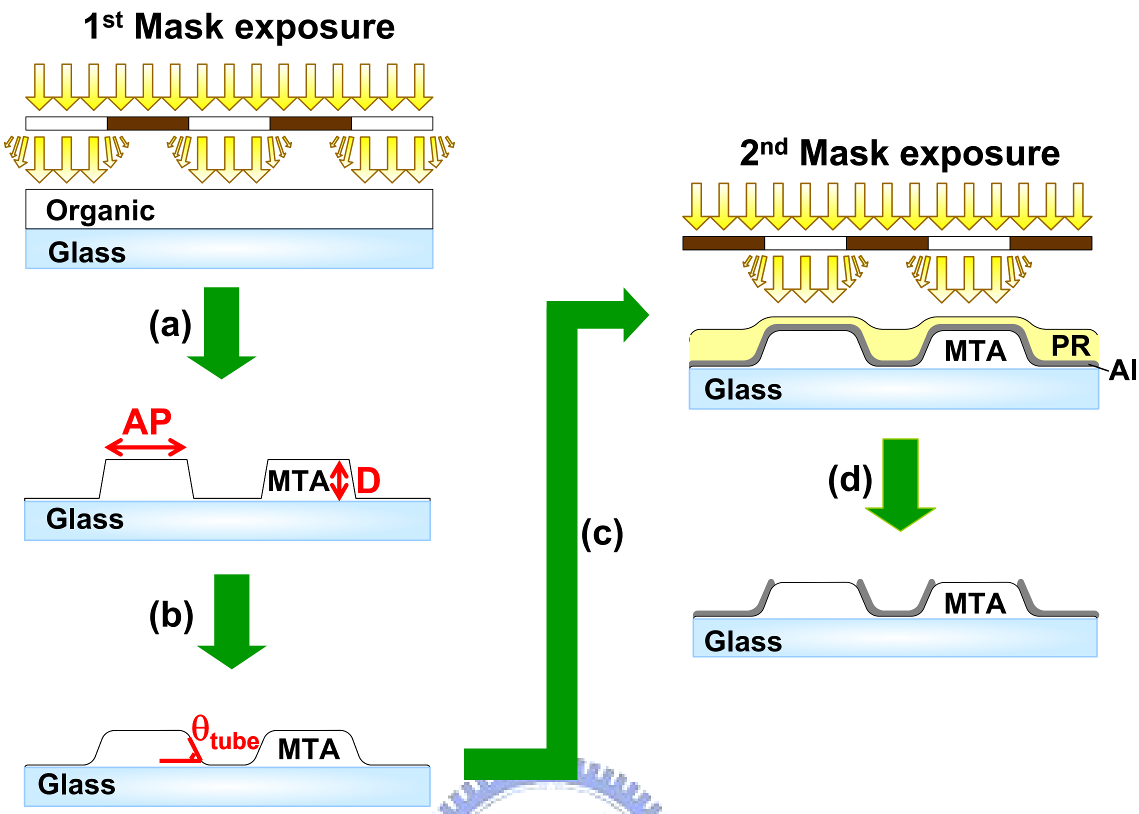


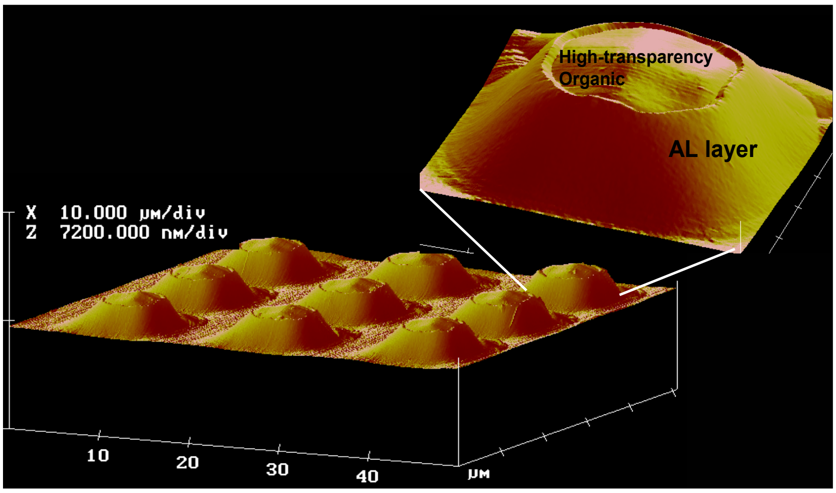
Fig. 6-8. The flowchart of fabrication process of the microtube array: (a) exposure of 1st mask, (b) thermal reflow process, (c) exposure of 2nd mask, and (d) removal of remaining photoresist and Al on upper aperture.

6.4.2 Evaluation of morphological and optical properties

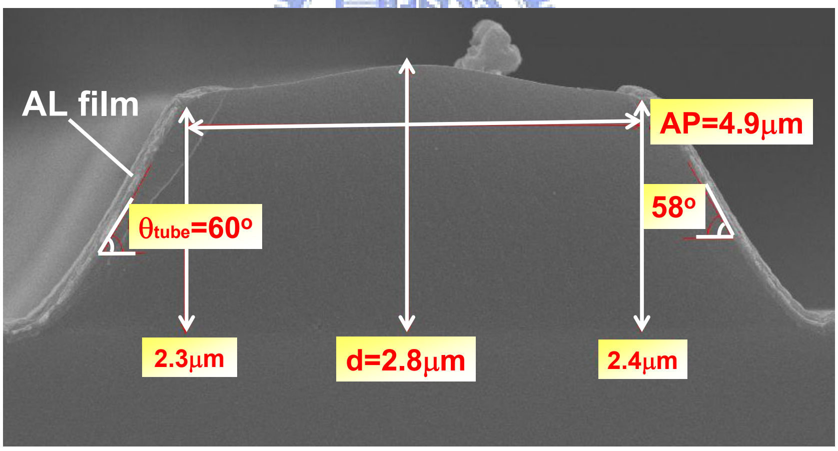
The surface structure and cross-sectional profile of the MTA were examined using an atomic force microscope (AFM) and a scanning electron microscope (SEM). The backlight utilization efficiency and enhancement of transmissive backlight were measured using ELDIM EZContrast 160R.

6.5 Results and discussion

The surface profile and optical performance of the fabricated MTA structure were measured. Figs. 6-9(a) and (b) depict the 3D view and the cross-sectional profile of the MTA, respectively, where a tube height (d) close to 3 μm, an upper aperture (AP) of about 5 μm and a tilt angle (θ_{tube}) of almost 60° were measured. These values satisfied the optimized values determined by the simulation.



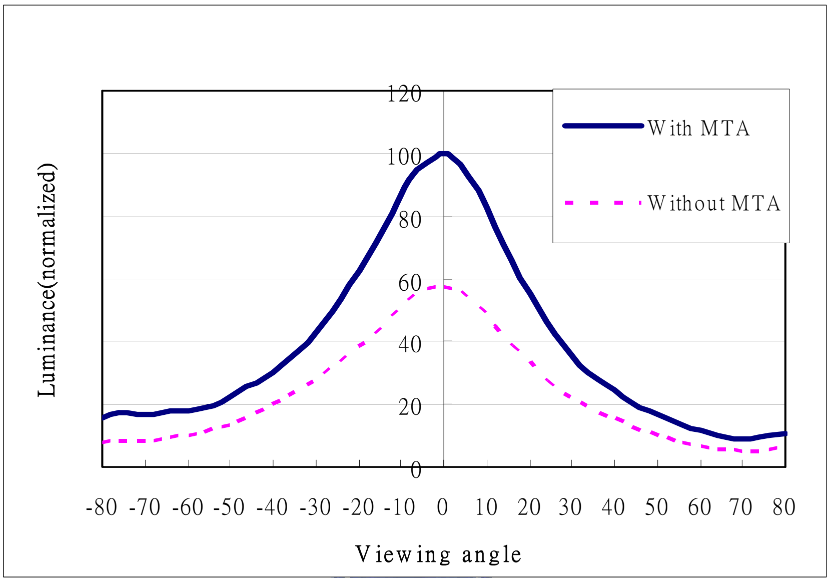
(a)



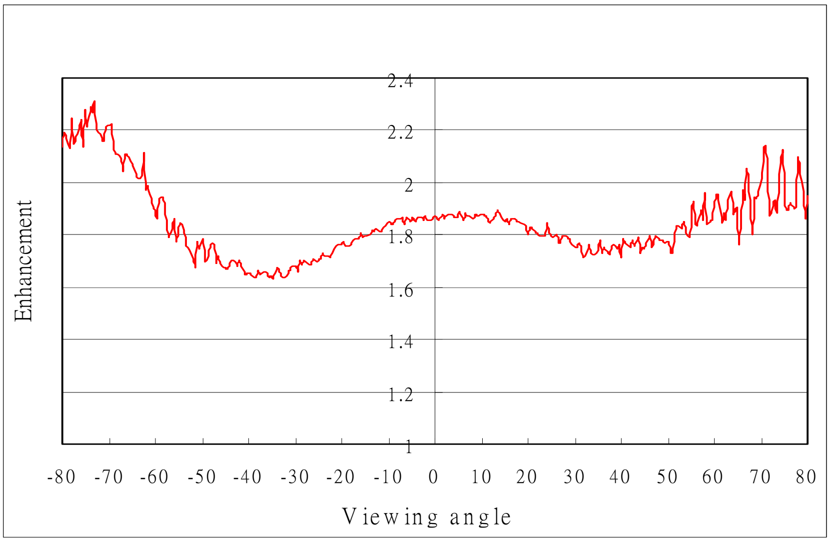
(b)

Fig. 6-9. The fabricated structure observed by (a) SEM and (b) AFM.

The relationship between the normalized luminance and viewing angle for structures with the MTA (solid line) and without the MTA (dash line) illuminated by conventional backlight is presented in Fig. 6-10(a). The structure with the MTA clearly has enhanced luminance at all viewing angles. This confirms the capability of collecting backlight for the MTA. Furthermore, the data are utilized to calculate the relationship between enhancement and the viewing angle shown in Fig. 6-10(b), where the measured backlight efficiency enhancement at different viewing angles is a factor of 1.65 to 2.3, and the averaged enhancement is a factor of 1.81, which is in agreement with the simulated results shown in Fig. 6-5 with AP=5μm, θ_{tube}=60° and average d=2.5μm.



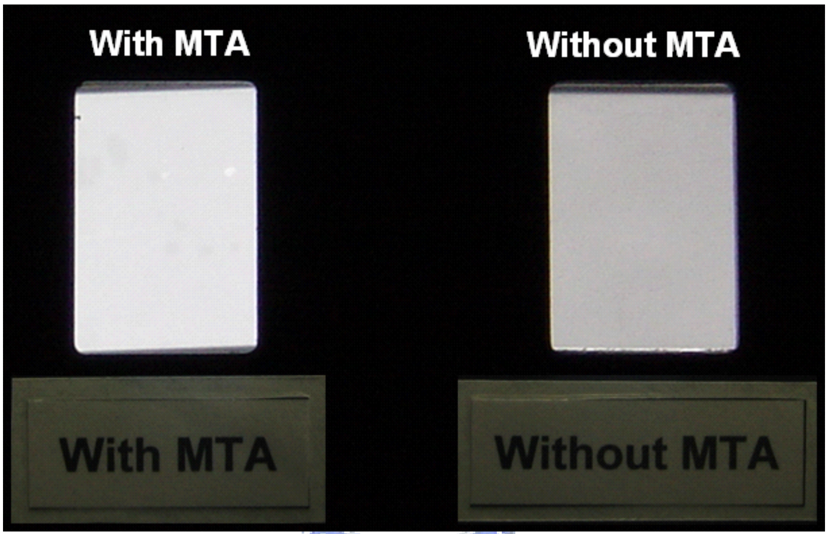
(a)



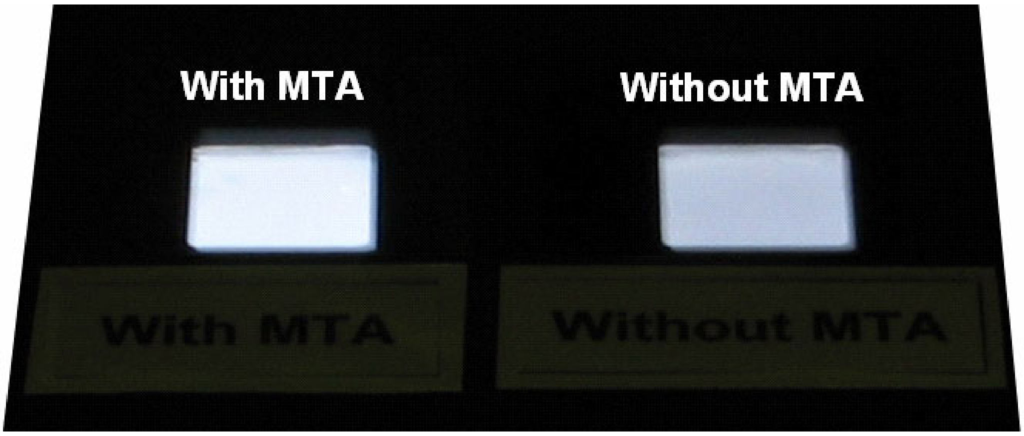
(b)

Fig. 6-10. Measurement results of (a) luminance and (b) enhancement as a function of viewing angle for microtube array structure.

Additionally, a transflective LCD with and without the MTA structure viewed from normal and oblique directions are respectively shown in Figs. 6-11(a) and (b), where there is a significant difference in the brightness at large angles. Furthermore, the proposed transflective LCD with the MTA structure can be fabricated by a typical TFT-LCD process.



(a)



(b)

Fig. 6-11. Photographs of a transflective LCD with and without MTA structure viewed from (a) normal and (b) oblique directions. (Color photos are shown in appendix)

6.6 Summary

In conventional transflective LCDs, the reflective region blocks most of the backlight from illuminating LCD's, thus reducing the backlight utilization efficiency. In order to overcome this issue, a novel structure, the MTA, which allows almost all backlight to enter the lower (larger) apertures and exit from the upper (smaller) apertures, has been demonstrated to collect more light to substantially increase the backlight utilization efficiency.

A prototype MTA was fabricated by a typical TFT-LCD process. The measured backlight efficiency enhancement at different viewing angles was a factor of 1.65 to 2.3, and the averaged enhancement was a factor of 1.81. As a result, the inclusion of the MTA structure can effectively increase the backlight utilization efficiency. Moreover, the enhancement allows the area ratio of the reflective region to the transmissive region to be redefined, which will enable the enhancement of the image quality. In addition, a backlight system with a lower power can be utilized to achieve the same illumination as in conventional transflective LCDs. Consequently, the novel transflective LCDs with the MTA can achieve reduced power consumption and high image quality, which are appealing in the mobile display market.