LCD BACKLIGHT OPTICS

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Optics of edge-lit backlight units (BLUs) for liquid-crystal display (LCD) are discussed in this paper. To control the direction of light in a BLU, micro-structures that their functions are based on the total internal reflection and the refraction of light are introduced. The light controlling features such as optical micro-reflectors, micro-deflectors, micro-polarizers are used on the surfaces of the light-guide plate (LGP) to shape and squeeze the light cone on the BLU. By applying the micro-features the emergent light can be directed effectively toward the LCD. These BLUs are used in video cameras, cellular phones, car navigation modules, netbooks, notebooks, monitors, TV sets, and in small size auto-stereoscopic 3D displays as well as light scanning LC devices.

Keywords: Liquid-crystal panel, LCD, backlight unit, BLU, light-guide plate, LGP, optical micro-reflector, optical micro-deflector, optical micro-prism.
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1. INTRODUCTION

Liquid-crystal displays (LCDs) play a leading role out of various flat-panel electronic display devices, because of their excellent features such as a low power-consumption, low operating-voltage, higher resolution, full color display capabilities, large area and lightweight.

LCD is an electro-optical effect based spatial light modulator. In order to recognize the image on the LCD display a backlighting apparatus, *i.e.*, backlight unit (BLU) is required. The light generated in BLU is transmitted through the LCD and is spatially modulated by each pixel in the panel which is recognized as an image. Since LCDs have light weight, thin structure and low power consumption, LCDs are widely applied as display devices for products as cell phone, netbook, video camera, digital still camera, car navigation system, personal computer, desktop monitor, and TV set.

Mainly two structures are being used in BLUs for illuminating the LCD panels. The first one is the edge-lit (edge light) or side-light type that uses a light-guide plate (LGP) and the second one is direct view type that uses a light chamber. Light-guide plate is an important component in light controlling in an edge-lit BLU and in the same manner a light chamber is important component in direct view type BLU [1].

By using an LGP in an edge-lit BLU one can obtain a thin BLU with high luminance uniformity than the direct-view BLU. In early period of LCD panel the direct view BLUs were used. However, the demand for thinner structures boosted the usage of LGP, *i.e.*, the edge-lit type. Currently the main stream of the BLU for LCDs is the edge-lit type, and direct view type is used in large sizes.

2. LCD STRUCTURE

The basic structure of an edge-lit type backlight is shown in fig.1 (a). In this type of BLU the light control medium, *i.e.*, the LGP is an optical transparent resin, *e.g.* Polymethyl Metacrylate (PMMA), Poly Carbonate (PC), or Cyclic Olefin Polymer (COP). The LGPs are formed into a slab shape or single wedge shape. For inserting the light into the LGP, light-emitting diodes (LEDs) or cold cathode fluorescent lamps (CCFLs) are used as light sources near to one to four sides of the LGP [1].

3. LIGHT DIFFUSING FEATURE; DIFFUSING DOTS

The silk screen method has been used to print light diffusing dots on the back surface of the LGP in the conventional light guide patterning as shown in fig.1 (b). From hereafter the surface of the LGP without any feature is defined as “mirror” (M) surface and the ink-printed surface are defined as “ink” (I), so that to name the LGP as “MI-LGP” as shown in the figure. [1, 2]

In general the ink used in the pigment of printing of the LGP is Titanium Dioxide (TiO_2) that possesses high optical refractive index. The pigment includes drying solvent as main medium. Another option is to use curable ultraviolet medium with the pigment. To achieve high optical reflection in the LGP spherical beads with irregular size are used in the pigment.

Luminance uniformity on the LGP is designed by changing the size of the printed dots, *i.e.*, having a gradation of dot diameter in which the dot diameter increases at distances far from the light sources. The shape of printed dot can be a circle, square, rectangle, or diamond. These dots are positioned at the corners of hexagon shape to achieve the maximum fill factor. For example, in a 6-inch/15.24 cm diameter LGP with 3 mm thickness, the printed dispersing dot on the back surface of the LGP is a circle with a size of 200 μm near to the light sources, and 600 μm at a position far from the light sources. When the size of light dispersing dot is large, the dot is recognized from the front surface of the LCD, depending on the thickness of the LGP. Recognition of the dispersive dots can be seen in the early (1960-1980) types of the liquid-crystal displays.

In a silkscreened LGP the propagating light inside the LGP repeats the internal reflection on the inner surfaces of the LGP and the light is dispersed when hits the dots. This leads to light dispersion and color non-uniformity in the BLU. When a light source with three primary colors or a pseudo-white color is used, white light is extracted on the LGP near the light sources and reddish light at positions far from the light source. The short wavelengths such as blue and green are scattered by the printed dots. These colors are gradually removed from the propagating light. This phenomenon is the so-called sunset light dispersion that exists in the light diffusing LGPs.

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4. LIGHT DIFFUSING FEATURE; MICRO-DIFFUSER

To avoid the time-consuming printing process more efforts have been put in chemical etching of the injection metal mold tool in which an optical flat surface of a mold that is used as back surface of an LGP in injection, is designed to have a pattern with etched (E) feature. The metal mold is used in a cavity on injection machine. The hot resin is shaped in the injection cavity and the pattern is transferred on to the resin to make an LGP with etching features [1, 2]. As shown in fig.1(c), the etching features are transferred onto the back surface of the LGP, and the front surface of the LGP is flat, *i.e.*, "mirror-like", so that the LGP is defined as "ME-LGP". To extract part of the propagating light from the LGP a uniform replication pattern of the etching features fabricated on an etched metal mold and is transferred onto the front surface of LGP in an injection mold. If the both the front and back surfaces of an LGP are replications of the etched features, the LGP is defined as "EE-LGP", *i.e.*, "Etching-Etching" LGP.

The size of an etching feature is about 200 μm. For making uniform luminance on the BLU, a density gradation of etching feature is applied to LGP in which the distance between the features decreases as the distance from the light sources increases. This is shown in fig.1 (d). In case of "EE-LGP", the front surface pattern is a uniform, *i.e.*, the distance between the etched dots is constant. However, to avoid interference between the LGP pattern and the prism films that are used on the LGP, the dot position is randomized frequently. By using the precisely etched molds and replication process, (injection mold), the time spending for printing, can be saved. In addition, the issues regarding the pigment density differences or diffusing feature size can be avoided.

To increase the diffusing function of the LGP, micro-size diffusing beads are added to the material of the LGP. Another option is to make fine diffusing features on the front surface of the LGP. This can be realized by replication of a diffusing mold pattern onto the LGP's front surface [3].

The LGPs explained in this section are light diffusing types in which one or two surfaces (front and back surfaces) of the LGP are replication of the etching feature. In a diffusing LGP the direction of the dispersed light is not controlled, thus resulting in light loss in the BLU.

To enhance the luminance on the LGP a light direction controlled LGP that can collimate the extracted light into a narrow light cone is required.

5. LIGHT REFLECTING FEATURE; MICRO-REFLECTOR

To control the direction of the extracted light and avoid issues of chemical etching, a TIR based micro-reflector has been developed. LGPs with optical micro reflectors (MRs) are shown in fig.2 [1, 4-6]. An MR feature has a shape of micro-lens or micro-prism with optical surface. The MR features are structured on the back surface of an LGP [7-16]. Each MR feature reflects light based on the total internal reflection (TIR).

To provide a uniform extracted luminance on the BLU, an array of MR features are fabricated on a metal mold with an optical surface. The pattern of the mold is transferred onto a LGP in an injection molding. The MR feature is often a concave or convex micro-lens with round, square, elliptical or diamond geometrical shape [1, 8]. An MR feature reflects substantial portion of the rays that are incident on the inner surface of the feature. A portion of the light rays that could not satisfy the TIR condition is refracted on the inner surface of the feature. The refracted light leaks toward the back surface of the feature. A reflector film is used near to the features to reflect back the leakage light into the LGP (fig.1).

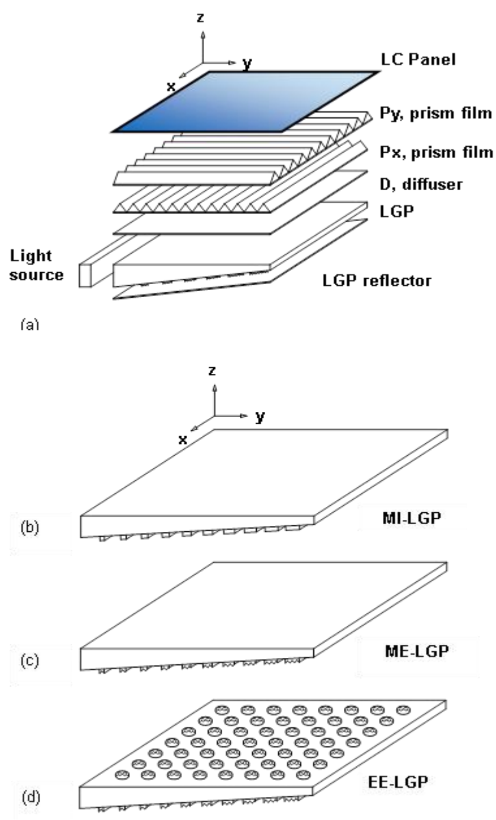

Fig.1. (a) is structure of a conventional LCD BLU. The LGPs with light diffusing features are shown in (b), (c), and (d). *(b)* is LGP with light diffusing printed (silkscreened) dots. *(c)* is LGP with replicated light diffusing dots. *(d)* is LGP with replicated light diffusing dots on the front and back surfaces.

Since the front surface of the LGP is "mirror-like" (M) and the back surface is a density gradation (G) of the MR features, the LGP is defined as "MR_G-LGP". In case of uniform pattern of MRs with constant pitch, the LGP is "MP_U-LGP". To enhance the TIR function of the MRs the tangent of the concave surface or the angle of reflection should be kept constant, *i.e.*, the surface should be as close as to a "V" shape prism surface.

To boost the collimation of the extracted light on the LGP, an array of micro-lines with "V" shape is fabricated on the back surface of the LGP. In this case the LGP is defined as "MP-LGP". The function of the MR feature is to reflect the propagating light without losing the light energy and to direct the extracted light into a light cone (solid angle). By controlling the reflection angle of the features the emergent light cone angle is controlled resulting in an increase of luminous flux and luminance on the BLU.

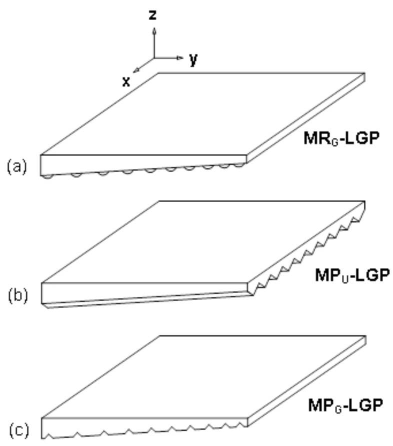

Fig. 2. LGPs with light reflecting features. *(a)* is LGP with omni directional MR_G features. *(b)* is LGP with uniform light collimating prism array along y-axis. *(c)* is LGP with graded position for linear prism along the x-axis.

The size of the MR feature is about few microns and in comparison with light diffusing dots or etching features, the MR features are small and not recognizable from top of the BLU through the LC panels.

Figure 3 shows cross-sections of the prismatic MR features that are often used to extract the light in LGPs. Depending on the shape of the prism, the zenith angles (with respect to LGP's surface normal) of extracted light rays increase. When the prisms shown in fig.3 (a), (b) are used, the emergent light have a large zenith angle on the LGP. The BLU structure and the light deflection concept are shown in fig.4 (a) and (b). Therefore, a prism film with total internal reflection (TIR prism), the so-called inverted prism, is required on the LGP to direct the emergent rays toward the normal surface of the LGP [17]. The prism structure shown in fig.3(c)-(f) extracts the propagating light rays toward the normal in which the zenith angles are reduced. To provide a uniform luminance, two methods are mainly used. In the first method, the prism angle is fixed and the pitch is varied. In the second method the pitch is fixed and the prism angles are varied. The parameters given in the figure are important for fixing the shape of the prism or designing a pitch gradation of the prisms. A graded-pitch prismatic LGP can be designed to have small emergent zenith angle for the extracted light. Such a prismatic LGP can be used with a low haze diffuser film without using any light directing or collimating film. The light cone of such a LGP is narrower than the light diffusing type LGP. When the prismatic MR features are used as light extraction, the light diffusion or wavelength dispersion is absent in the LGP.

6. LIGHT DEFLECTING FEATURES; MICRO-DEFLECTOR

To provide a direction controlled light cone on the front surface of a LGP, the MR features shown in fig.3 are structured on the back surface of the LGP [1]. Figure 5 shows the LGPs with light ray micro-deflector (MD) on the front surfaces. The MD features are being fabricated on the mold tools similar to that of MR feature and are being transferred to a LGP using injection molding.

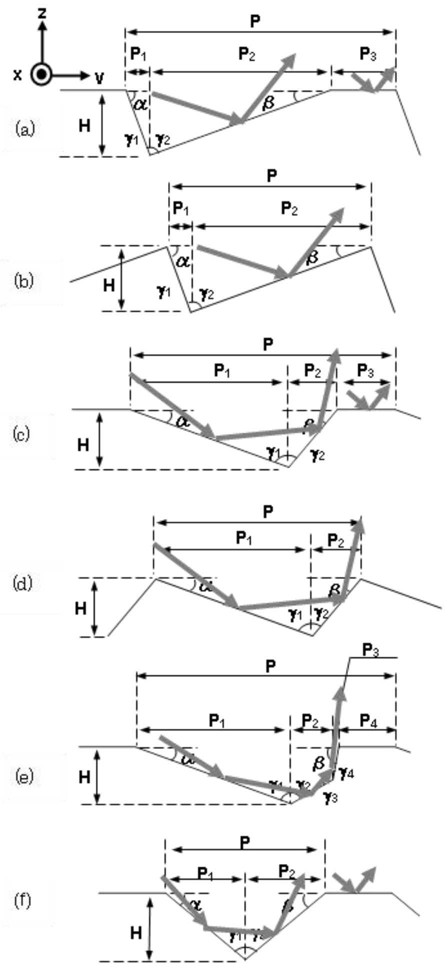

Fig.3. (a) Prism structures for light extraction. *(b)* Prisms that extract the light in a way that the zenith angle of the emerged light increase with respect to the surface normal. *(c), (d), (e), and (f).*The prisms that extract the light in a manner that the zenith angle decrease with respect to surface normal.

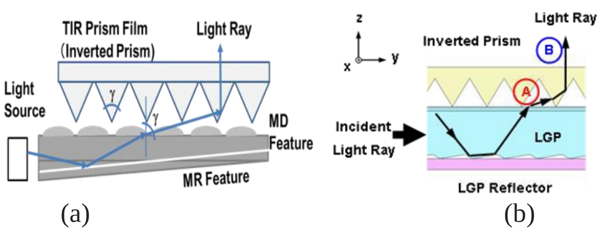

Fig.4. Principle of light ray deflecting in a BLU with functional LGP and inverted prism film. *(a)* BLU cross section, *(b)* Light deflection concept.

In a MD-LGP a light ray repeats total internal reflections before hitting a single MD feature. When a ray is incident on the inner surface of a MD feature, the ray is deflected (on refraction) and directed on the MD feature. To form the emergent light cone and to control the light direction, the geometrical shape of the micro-deflector feature is designed and matched to the MR feature.

In the design of a LGP the required emergent light can be assumed and the arrays of micro-reflectors and micro-deflectors are designed in combination.

7. LIGHT POLARIZING FEATURES; MICRO-POLARIZER

A micro-prism shaped on the back surface of LGP separates the propagating light into reflecting and refracting light [1]. As shown in fig.6, the incident light onto the prism surface is polarized into S-polarization, perpendicular to the incident surface, and P-polarization, parallel to the incident surface. The reflection factors for these polarizations are different. However, when the reflection factor of the P-polarization approaches to zero, the incident angle is the so-called Brewster angle. Under the Brewster condition the reflected ray is perpendicular to the refracted light ray, *i.e.*, the angle between these two rays is 90° ($\theta_r + \theta_t = 90°$), where the incident angle is θ_i, the reflection angle is θ_r, and the refraction (transmitted) angle is θ_t. The Brewster angle is given by $\theta_B = tan^{-1}[1/n(\lambda)]$, where the refractive index of the prism material is $n(\lambda)$. In case of PMMA, the refractive index $n(\lambda_D)$ is equal to 1.492 at D-line (λ_D=589.3 nm) of the Sodium and the Brewster angle is about θ_B=33.8°. The Brewster polarization angle is defined for a single light ray. Therefore a portion of the propagating light rays can satisfy the polarization condition. The prism with Brewster angle can be designed by considering the propagating rays angles'.

8. LIGHT SHAPING FEATURES ON INCIDENT PLANE; ROUNDED MICRO-PRISM

In an edge-lit type BLU few LEDs or tens of LEDs are used near to the light introduction surface (one of the sides) of a LGP depending on the application, the size, the amount of luminance, or an optimized angular luminance distribution [18]. When the light introduction surface of an LGP is flat, the introduced light of the LED is being refracted on the light introduction surface and as a result the rays are being deflected toward the surface normal on the inner surface (light introduction surface). The maximum possible angle of an introduced ray is corresponding to the critical angle $\theta_C = sin^{-1}(1/n_{LGP})$, where n_{LGP} is the refractive index of the LGP. The light distribution inside the LGP is limited within the critical angles cone and a dark zone appears between two internal distributions (between two LEDs). The zone contributes in non-uniformity of the luminance distribution on the BLU. To reduce or eliminate the non-uniformity, an array of micro-structures (rounded micro-prism) are fabricated on the light introduction surface to widen the internal light distributions, or increase the refracted light cone as shown the structures in fig.7. The array of micro-structures widens the light distribution inside the LGP that results in reducing the dark zone and increasing uniformities on the LGP. The light distribution cone is limited to about +/-42° (n_{LGP} =1.492, PMMA) when the light introduction surface is flat. However, when the rounded micro-prisms are used on the light introduction surface the distribution is widened to +/-57° (fig.8). By providing the micro-structures, the inserted light increases that results in reducing the Fresnel loss and an increase in coupling efficiency by 5%. For comparison the coupling efficiency for a slab LGP is about 82%.

9. LIGHT SHAPING FEATURES ON INCIDENT PLANE; LENTICULAR LENS ARRAY

To shape and to control the direction of the light inserted into the LGP, an incoherent diffraction grating is structured on the back surface of the LGP near to the light introduction surface as shown in fig.9. As an example a grating with a pitch of P=240 μm, a width of W=120 μm, a height of H=32 μm, a radius of R=72 μm, a length of L=2 mm is designed in an LGP with a thickness of t=0.8 mm for cell phone BLU application. The thickness

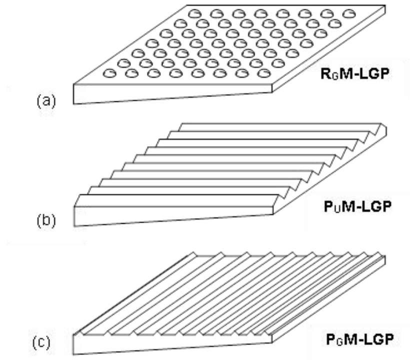

Fig. 5. LGPs with light deflecting features.*(a)*is Omnidirectional features, *(b)* is uniform unidirectional light deflecting features, *(c)* is position-graded light deflector features on the front surface of the LGPs.

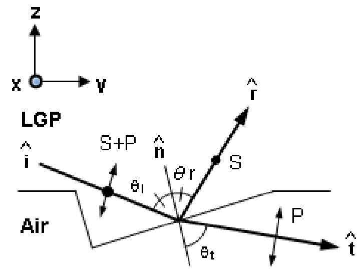

Fig.6. Light polarizing feature. The polarizing features separate the S is wave and P is wave on reflection. These are structured on the back surface of the LGP.

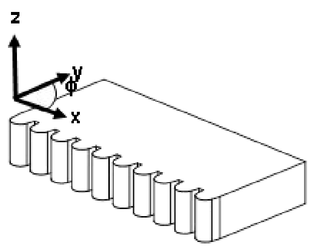

Fig.7. Micro-optical features on the light introduction surface of the light-guide plate. These structures widen the spatial light distribution of the inserted light inside the LGP.

or the number of the LEDs is the parameters in designing of the gratings where the size can be few microns to tens of microns. In addition, the shape can be "V" prism, rounded prism or lenticular lenses depending on the distribution of the inserted light on the inner surface of the light introduction surface. Due to the shape of the gratings the light can be directed toward sides of the LGP or toward the surface on the opposite surface (against the light source). The gratings shape the propagating light and as a result shaping the emergent light on the LGP. Therefore, the dark zone reduces and leads to decrease in the dark zones, *i.e.*, an increase in the bright area, and finally an increase in the uniformity near the light source on the LGP.

10. LIGHT SOURCES FOR BACKLIGHT; PSEUDO-WHITE LED

An LED is a solid-state lighting feature that is based on the PN junction of gallium nitride (GaN) compound semiconductor light-emitting material [1]. A pseudo-white LED is a combination of Indium mixed GaN that has a light emitting quantum well structure, and YAG phosphor layer that covers the semiconductor chip (fig.10).

A pseudo-white LED is based on phosphor excitation and wavelength conversion. The chip emits blue light that excites the surrounding phosphors layer of yellow light. The blue light is scattered and absorbed by the phosphor. Since the blue and yellow light are complementary colors, the result of color combination is a white color.

In recent years, the pseudo-white LEDs are widely used in the backlights of the handy terminals, such as cell phones, netbooks, and notebooks computers. Top-view LEDs are used in car navigation systems and side view LEDs are used in notebook PCs and netbooks. By using these small pseudo-white LEDs, thin and light weight units and modules are realized. The LEDs are being merged into the display backlight of various sizes. Therefore, the demands for LEDs with higher efficiencies and different packages are widely highlighted.

High efficiency monochromatic LED light sources of red (R), green (G) and blue (B) have been developed in recent years, and used as primary colors in LCD backlighting unit. Blue and green are the chips of compound semiconductors of InGaN, and red LED is a compound of four semiconductors, *i.e.*, AlInGaP (Aluminum, Indium, Gallium, and Potassium). These LEDs are used in a backlight and a white point is obtained based on the additive color mixing. Because of the large dependency of the LEDs on the temperature, a light sensor is installed in the BLU to stabilize the BLU, especially in large size displays. The three-primaries used BLUs have wide color production gamut that can be used in the applications of image editing and design. However the tolerances between colors of the LEDs or low electro-optical conversion efficacy and high cost of the LEDs, are the barriers in employing of the LED with primary colors to display backlights. Despite of great attempt to use primary colors in BLUs, Sony Corporation announced all LED display in Los Vegas Consumer Electronic 2012.

11. LIGHT SOURCES FOR BACKLIGHT; COLD CATHODE FLUORESCENT LAMP

A cold cathode fluorescent lamp (CCFL) was being used in large size LCD displays until the recent years. A CCFL is made of two electrodes mounted at each side of fluorescent glass tube of any shape, includes an appropriate amount of Mercury (0.5-1.0 mg) and encloses an inert gas (Argon). The fluorescent materials include three wavelengths phosphor that is coated on the inner wall surface of the tube [1]. When a high voltage is applied between the electrodes, the electrons are drawn toward the electrodes present inside the tube as shown in fig.11. The electrons collide with the mercury molecules in the tube and as a result of collision ultra violet light is emitted. The ultraviolet light excites the phosphor that leads to white light conversion.

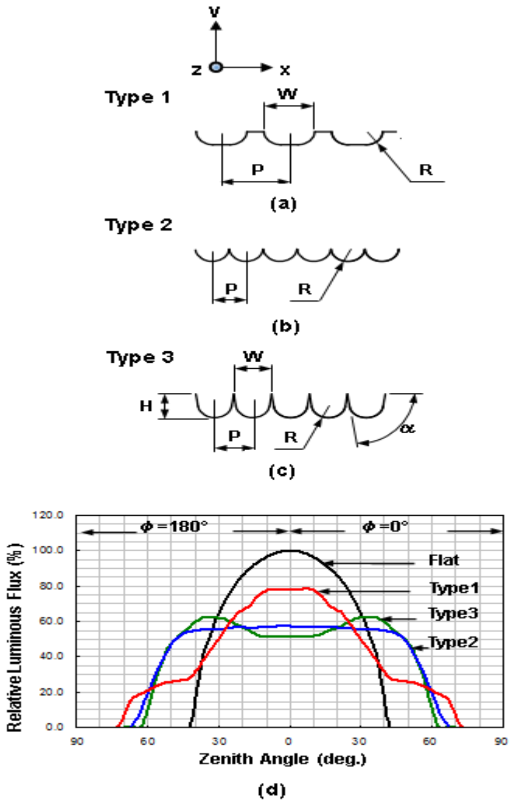

Fig.8. Structures used on the light introduction surface of a LGP for light shaping inside the LGP. *(a)*,*(b)* and *(c)* are cross-sections of three types of features. *(d)* is light intensity distribution in a LGP using the features shown in (a), (b) and (c). Flat is the surface without micro-structure that is shown for comparison.

The CCFLs of 3 mm in diameter were used in the large TV sets or monitors. However, the recent movements on prohibition of the mercury which is a toxic material, and the recent development of high efficacy pseudo-white LEDs boost the usage of the LEDs in the display BLUs.

12. CONCLUSIONS

A backlight functions as illuminant unit at the rear of liquid crystal panel and plays an important role in reducing power consumption and improving the display characteristics. The advances in light emitting devices, their driving methods and the function of a light-guide plate that configures a backlight are explained in this paper.

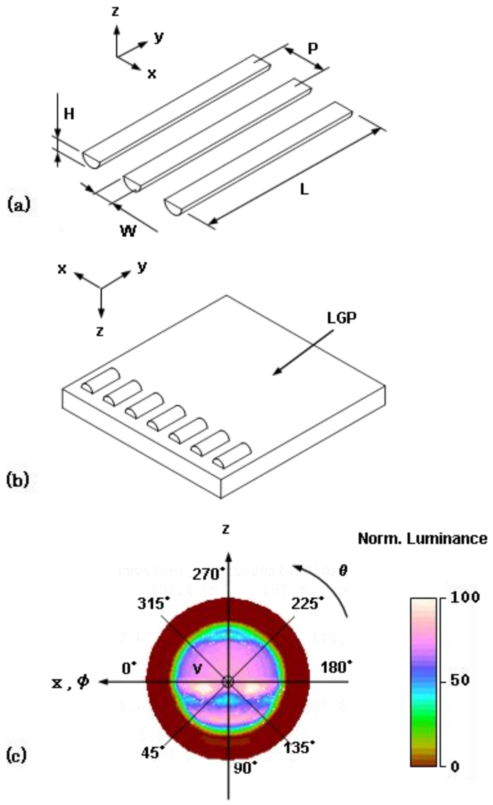

Fig.9. Structures used on the light introduction surface of a LGP for light shaping inside the LGP. (a),(b) and (c) are cross-sections of three types of features. (d) is light intensity distribution in a LGP using the features shown in (a), (b) and (c). Flat is the surface without micro-structure that is shown for comparison.

A light-guide plate is used not only to make a uniform luminance but also for dispersing, reflecting, deflecting or shaping the emergent light. A backlight unit with a wide angular luminance distribution can be realized by using a light dispersing LGP. A backlight unit with controlled angular luminance distribution can be obtained by employing a LGP that is featured by micro-reflector features [19-22]. The angular luminance can be squeezed by combining the light deflecting and the micro-reflecting features in a LGP [20,22]. A variety of light shaping BLU can be realized by selecting proper light reflector and deflector features.

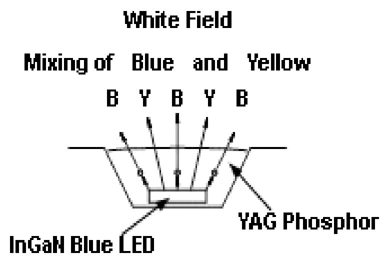

*Fig.10.*Pseudo-white LED. A blue light emitting chip (InGaN) is covered with the yellow fluorescent agent; YAG. The additive complementary colors mixing result in white color light.

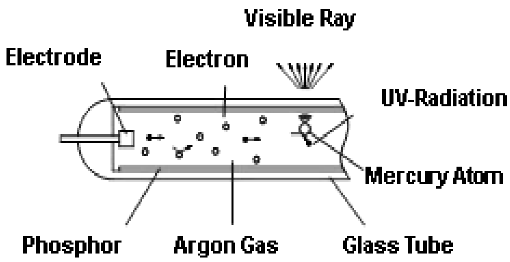

Fig.11. Structure of a CCFL. Small amount of Mercury (0.5-1.0 mg) and inert gas (Argon) are encapsulated in the tube.

In the near future, the divergence applications of versatile LCD are expected. Therefore, a thin and highly functional LGP that results in realization of low power consumption BLU is necessary.

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