Chapter 5
Backlights

Kälil Käläntär

5.1 LCD Backlight Unit

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5.1.1 Introduction

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

An LCD is a spatial light modulator based on the electro-optical effect. 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. LCDs are lightweight, have thin structure, and have low power consumption. Therefore, 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 a flat-screen TV.

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 direction controlling in an edge-lit BLU, and in the same manner a light chamber is important component in direct-view type BLU.

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N. Koide (ed.), *The Liquid Crystal Display Story: 50 Years of Liquid Crystal R&D that lead The Way to the Future*, DOI 10.1007/978-4-431-54859-1_5,

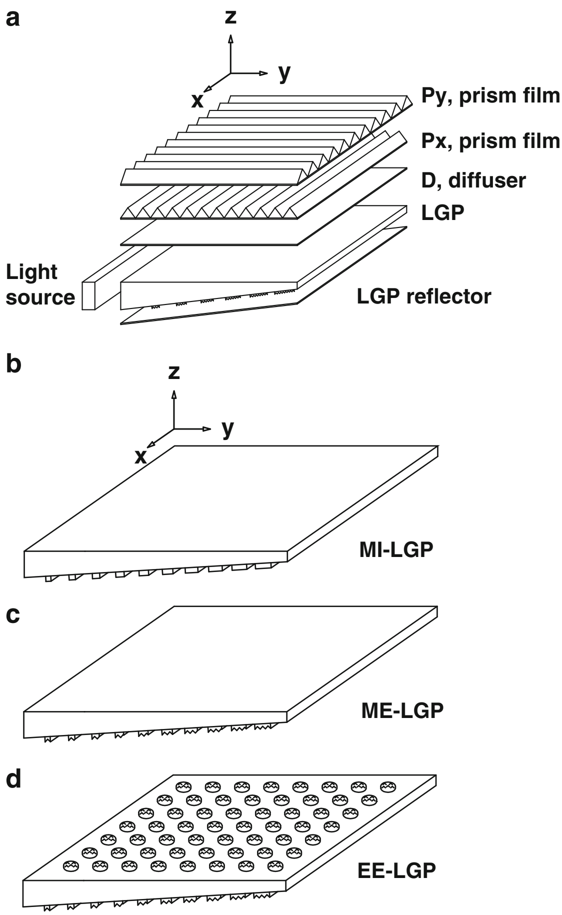

Fig. 5.1 (**a**) Structure of a conventional BLU and (**b–d**) are the LGPs with light diffusing elements. (**b**) LGP with light scattering printed dots. (**c**) LGP with replicated light scattering dots. (**d**) LGP with replicated light scattering dots on the front and back surfaces

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 the 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 mainstream of the BLU for LCDs is the edge-lit type, and direct-view type is used in large sizes.

5.1.2 LCD Structure and LGP Materials

The basic structure of an edge-lit type backlight is shown in Fig. 5.1a. In this type of BLU the light control medium that is the LGP is a transparent resin which is made up of polymethyl methacrylate (PMMA), poly carbonate (PC), or cyclic olefin polymer (COP). The LGPs are formed into a slab shape or wedge shape. The light-emitting diode (LED) or cold cathode fluorescent lamp (CCFL) are being used as light sources near to one to four sides for inserting the light into the LGP [1].

5.1.3 Light Diffusing White-Ink (Silkscreen) Printed LGP

The conventional light-guide patterning is a silkscreen method to print spots on the back surface of the LGP as shown in Fig. 5.1b. Here the surface of the LGP without any element taken as "mirror" (M) and the ink-printed surface are taken as "ink" (I), so that the LGP is named "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 refractive index. The pigment includes drying solvent as the main medium. Another option is to use curable ultraviolet medium with the pigment. For obtaining high reflection, irregular sizes of spherical beads are used in the pigment. High luminance uniformity is achievable by changing the size of the printed dots, i.e., having a size gradation in which the dot becomes large at distances far from the light sources. The shape of printed dot can be a circle, square, rectangle, or diamond. These dots are being positioned at the corners of hexagon shape, in which the maximum fill factor can be obtained. For example, in a 6 in. LGP with 3 mm thickness, the dispersing element is a circle with a size of 200 μm on the back surface of the LGP near to the light sources and 600 μm at a position far from the light sources. When the size of light-dispersing element is large, it can be recognized from the front surface of the LCD depending on the thickness of the LGP. Recognition of the dispersive spots can be seen in the early types of the LCD displays.

In this type of the LGP the propagating light inside the LGP repeats the internal reflection on the inner surfaces of the LGP and is dispersed by hitting the dots that leads to wavelength dispersion. When a light source with three primary colors or a pseudo-white is used, the white light is extracted on the LGP near the light sources and reddish light at positions far from the light source. The short wavelength components such as blue and green scatter more strongly by the printed spots. Thus, these colors are removed from the propagating light. This phenomenon is the so-called sunset light dispersion that exists in the light diffusing LGPs.

5.1.4 Light Diffusing Etched-Dot Replicated LGP

In order to avoid the printing process, more efforts have been put in the mold tool etching in which an optical flat surface of a mold is designed to have a pattern with etched (E) elements. The mold is used in a cavity on an injection machine. The hot resin is shaped in the cavity and the pattern is transferred onto the resin that makes an LGP [1, 2]. As shown in Fig. 5.1c, the etched elements are transferred onto the back surface of the LGP, and the front surface of the LGP is flat and "mirrorlike," so that the LGP is named "ME-LGP." To extract more light from the LGP a uniform replication pattern of an etched mold is transferred onto the front surface of LGP. If both sides of LGP are a replication of the etched elements, the LGP is named "EE-LGP."

The size of a light-dispersing etched element is about 200 μm and all the elements have the same size. For making uniform luminance on the BLU, a density gradation is applied in which the distance between the elements decreases as

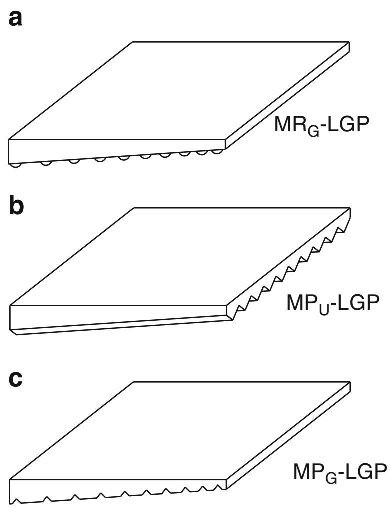

Fig. 5.2 LGPs with light reflecting elements. (**a**) LGP with omnidirectional MR_G elements. (**b**) LGP with uniform light collimating prism array along the *y*-axis. (**c**) LGP with graded position linear prism along the *x*-axis

distance from the light sources increases. This is shown in Fig. 5.1d. In case of "EE-LGP," the front surface pattern is 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 precise etched molds and replication process, the time spent for printing can be reduced. In addition, the issues regarding the pigment differences or diffusing element size can be avoided. To increase the diffusing function of the LGP, diffusing beads are added to the material of the LGP. Another option is to make fine diffusing dots 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 above are light diffusing types in which single side or double sides of an LGP are the replication of the etched dots. In a diffusing LGP the direction of the dispersed light is not controlled, thus resulting in light loss in the BLU.

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

5.1.5 LGP with MR Elements

LGPs with optical micro-reflectors (MRs) are shown in Fig. 5.2 [1, 4–6]. An MR element has a shape of a micro-lens or microprism with optical surface. The MR elements are structured on the back surface of an LGP [7–16]. Each MR element reflects light based on the total internal reflection (TIR). To provide a uniform extracted luminance on the BLU, an array of MR elements are fabricated on a mold with an optical surface. The pattern of the mold is transferred onto an LGP in an injection molding. The MR element is often a concave or convex lenslet with round, square, elliptical, or diamond geometrical shape [1, 8]. An MR element reflects substantial portion of the rays that are incident on the inner surface of the element. A portion of the light rays that could not satisfy the TIR condition is refracted on the inner surface of the element. The refracted light leaks towards the back surface of the element. A reflector film is used near to the elements to reflect back the leakage light into the LGP (Fig. 5.1).

Since the front surface of the LGP is "mirrorlike" (M) and the back surface is a gradation (G) of the MR elements, the LGP is named "MR_G-LGP." In case of uniform the pattern elements with constant pitch, the LGP is "MR_U-LGP." To enhance the TIR function of the elements, 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 prism surface.

To collimate the extracted light a uniform line prism pattern with constant pitch is structured on the back surface of the LGP. In this case the LGP is named "MP-LGP." The feature of the MR elements is to reflect the propagating light without any optical loss and direct the extracted light into a light cone. By controlling the reflection angle of the element the emergent light cone angle is controlled resulting in an increase of luminous flux and luminance on the BLU.

The size of the MR element is about few microns, and in comparison with diffusing printing or etching elements, the MR elements are small and not recognizable from top of the BLU or LCD. Figure 5.3 shows cross sections of the MR elements that are often used to extract the light. Depending on the shape of the prism, the polar angle of extracted light rays increases. When the prisms shown in Fig. 5.3a, b are used, the emergent light have a large zenith angle (the angle between the z-axis and the emergent ray direction) on the LGP. Therefore, a prism film with total internal reflection, the so-called inverted prism, is required on the LGP to direct the emergent rays towards the normal surface of the LGP [17]. The prism structure shown in Fig. 5.3c–f extracts the reflect light rays towards the normal in which the polar 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 angles varied. The parameters given in the figure are important for fixing the shape of the prism or making a gradation of the prisms. By using a diffuser film with low haze on the LGP, a BLU without prism film can be made.

When the MR elements are used as light extraction, the light diffusion or wavelength dispersion is absent in the LGP. The light cone of such an LGP is narrower than the light diffusing type LGP.

5.1.6 LGP with MD Element

To provide a direction controlled light cone on the front surface of an LGP the MR elements shown in Fig. 5.3 are structured on the back surface of the LGP [1]. Figure 5.4 shows the light guides with the microdeflector (MD) elements on the front surfaces. The MD elements are being fabricated on the mold tools similar to that of MR elements and are being transferred to an LGP using injection mold.

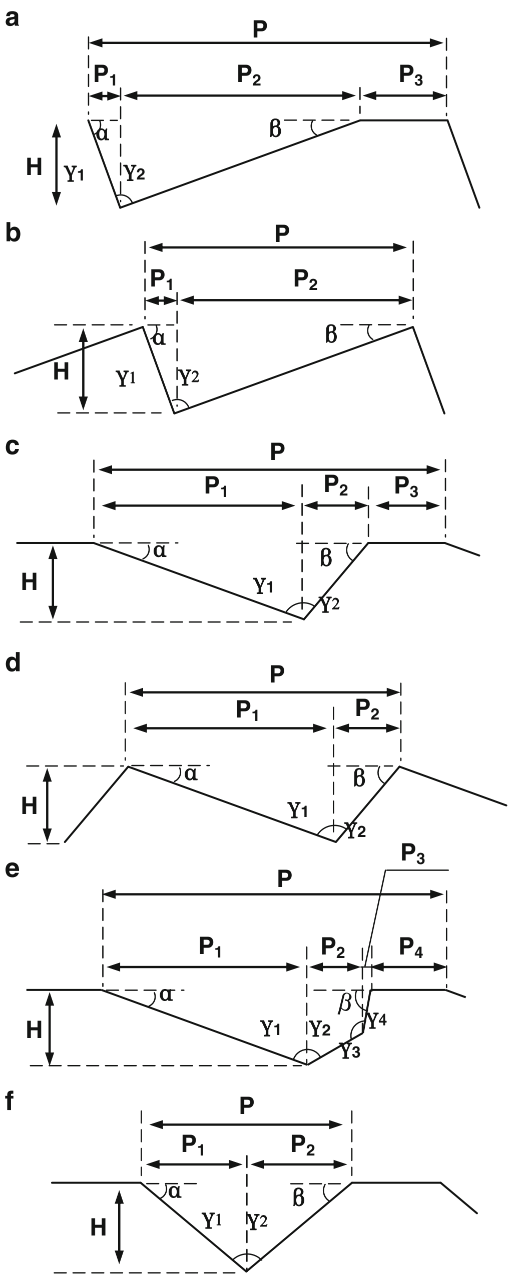

Fig. 5.3 Prism structures for light extraction. (**a**, **b**) Prisms that extract the light in a way that the zenith angle of the emerged light increases with respect to the surface normal. (**c**–**f**) The prisms that extract the light in a manner that the zenith angle decreases with respect to surface normal

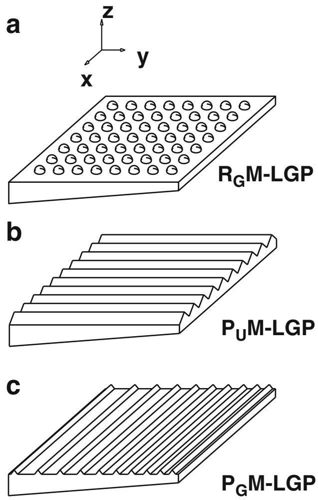

Fig. 5.4 LGPs with light deflecting elements. (**a**) Omnidirectional elements, (**b**) uniform unidirectional light deflecting elements, and (**c**) position-graded light deflector elements on the front surface of the LGPs

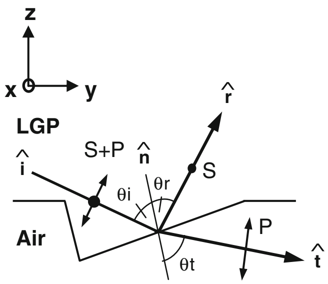

Fig. 5.5 Light polarizing element. The polarizing elements separate the S-wave and P-wave on reflection. These are structured on the back surface of the LGP

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

In the design of an LGP the emergent light is assumed and the micro-reflector and micro-deflectors are designed, respectively, in which the combination can provide the required light cone on the LGP. A proper gradation of the element positions can be designed and structured.

5.1.7 LGP with Light Polarizing Element

A microprism shaped on the back surface of LGP dispatches the internally reflected propagating light and the refracted light [1]. As shown in Fig. 5.5 depending on the angle of an incident light onto the prism surface, the light is being polarized into

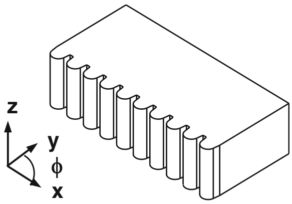

Fig. 5.6 Micro-optical elements on the light introduction surface of the light-guide plate. These structures widen the spatial light distribution of the inserted light inside the LGP

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. By defining the incident angle θ_i, the reflection angle θ_r, and the refraction (transmitted) angle θ_t, under the Brewster condition, the reflected ray is perpendicular to the refracted light ray, i.e., the angle between these two rays is 90° ($\theta_r + \theta_t = 90°$). 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 $n_D(\lambda)$ is equal to 1.492 at D-line (λ=589.3 nm) of the sodium and the Brewster angle is about $\theta_B = 33.8°$. 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 ray angles.

5.1.8 Light-Shaping Element

5.1.8.1 Shaping Light in an LGP with Microstructures on the Light Incident Plane

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 an 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 and as a result the rays are being deflected towards the surface normal. 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 refraction angle of the LGP. The light distribution inside such an LGP is limited within the critical angles and a dark zone appears between two internal distributions (between two LEDs). The zone contributes in the nonuniformity of the luminance distribution on the BLU. To reduce or eliminate the nonuniformity, an array of microstructures are fabricated on the light introduction surface to widen the internal light distributions as shown the structures in Fig. 5.6. The array of microstructures widens the light

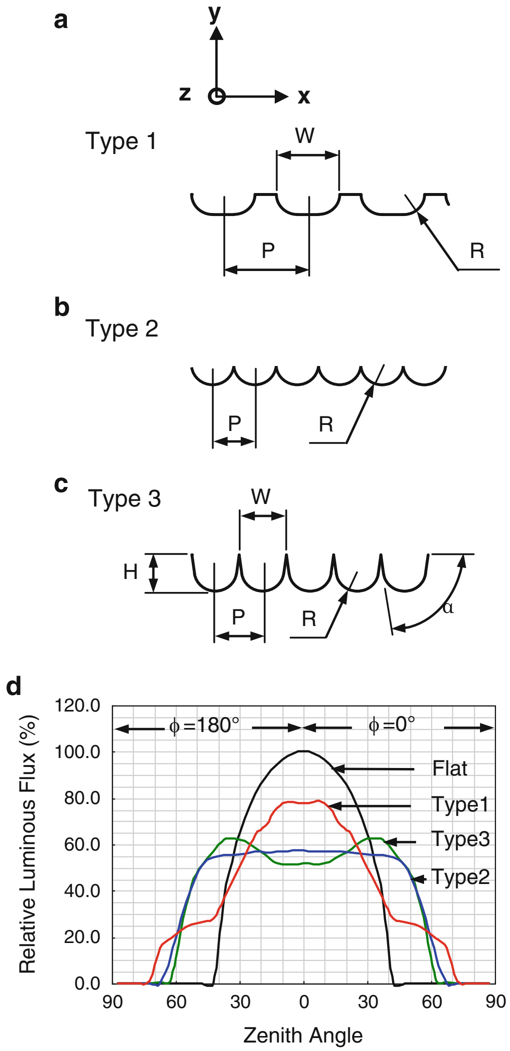

Fig. 5.7 Structures used on the light introduction surface of an LGP for light shaping inside the LGP. (**a**–**c**) The cross section of the three-type elements. (**d**) Light intensity distribution in an LGP using the structures shown in (**a**–**c**). Flat is the surface without microstructure that is shown for comparison

distribution inside the LGP that results in reducing the dark zone and increasing uniformities. The internal light distribution is limited to about ±42° ($n_{LGP} = 1.492$, PMMA) when the light introduction surface is flat. However, when the microstructures are used on the light introduction surface, the distribution is widened to ±7° (Fig. 5.7). By providing the microstructures the inserted light in coupling surface increases that result in reducing the Fresnel loss and an increase in coupling efficiency by 5 %.

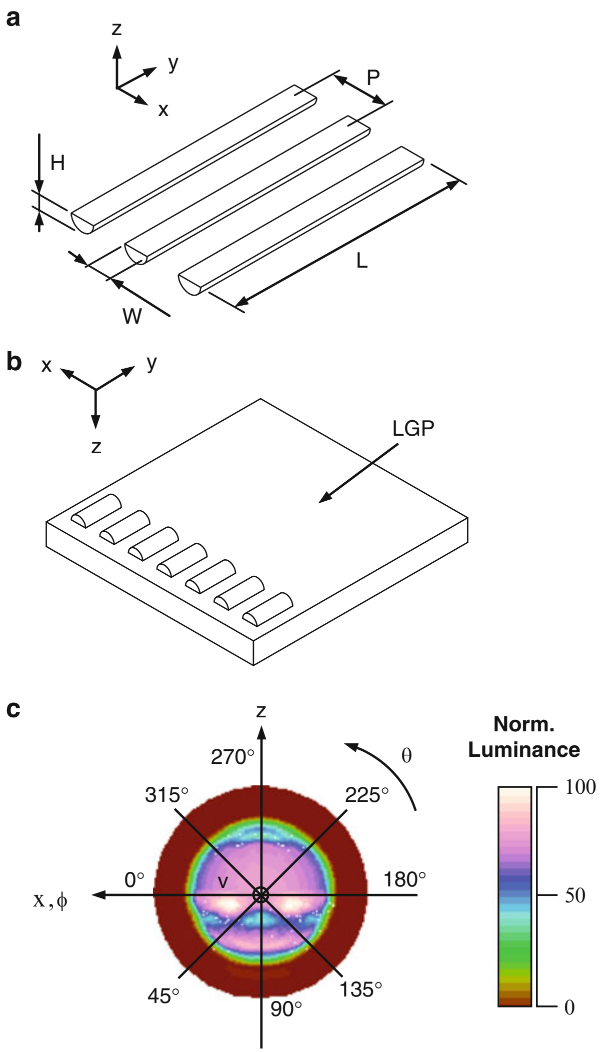

Fig. 5.8 Incoherent diffraction grating on the back surface of the LGP, near the light introduction surface, for forming the light inside the LGP. (**a**) Incoherent diffraction gratings, (**b**) The light-guide plate with rear gratings. (**c**) Light intensity distribution in the LGP observed on the *y*-axis (observing the far field pattern of the propagating light from a point against the light introduction surface)

5.1.8.2 Light Shaping in the LGP using Incoherent Diffraction Gratings

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. 5.8. As an example a grating of pitch $P = 240$ μm, a width of $W = 120$ μm, a height of $H = 32$ μm, a radius of $R = 72$ μm, and a length of $L = 2$ mm has been designed in an LGP with a micro-reflectors and a thickness of $t = 0.8$ mm that is used in a cell phone BLU. The thickness or the number of the LEDs is the parameters in designing of the gratings where the size

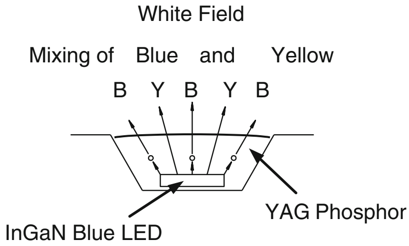

Fig. 5.9 A pseudo-white LED. A blue light-emitting chip (InGaN) is covered with the yellow fluorescent agent, YAG. The additive complementary color mixing results in white color light

can be few microns to tens of microns. In addition, the shape can be "V" prism or rounded prism 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 towards the sides of the LGP or towards the surface against the light source. The gratings shape the propagating light, and as a result it shapes the emergent light on the LGP. Therefore, the dark zone reduces and decreases, leading to an increase in the bright area and finally an increase in uniformity.

5.1.9 Light Sources for Backlight

5.1.9.1 Pseudo-White LED

An LED is a solid-state lighting element that is based on the PN junction of gallium nitride (GaN)-based compound semiconductor light-emitting material [1]. A pseudo-white LED is a combination of indium GaN that has a light-emitting quantum well structure and YAG phosphor layer that covers the semiconductor chip (Fig. 5.9).

A pseudo-white LED is based on phosphor excitation and wavelength conversion. The chip emits blue light that excites the surrounding phosphor layer of yellow light. The blue light is scattered and absorbed by the phosphor. Since the blue and yellow lights 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 notebook 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 lightweight units and modules are realized. The LEDs are being merged into the display backlight of various sizes. Therefore, the demands for higher-efficiency LEDs with different packages are widely highlighted.

In recent years, high-efficiency monochromatic LED light sources of red (R), green (G), and blue (B) have been developed 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

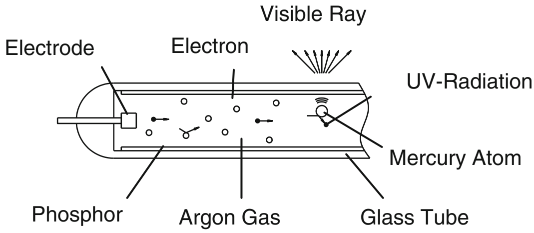

Fig. 5.10 Structure of a CCFL. Small amount of mercury (0.5–1.0 mg) and inert gas (argon) are encapsulated in the tube

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. The three primary used BLUs have wide color production gamut that can be used in the applications of image editing and design. However, the tolerances between some color LEDs or low electro-optical conversion efficacy and high-cost LEDs are the barriers in employing the primary LED colors in displaying backlights. Despite great attempt to use primary colors in BLUs, Sony Corporation announced all LED display in Las Vegas Consumer Electronic Show in 2012.

5.1.9.2 Cold Cathode Fluorescent Lamp

A CCFL that is used in large-sized LCD displays is made up of two electrodes mounted at each side of the fluorescent glass tube, of any shape, filled with mercury (0.5–1.0 mg) and an inert gas (argon). The fluorescent materials include three-wavelength 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 towards the electrodes present inside the tube as shown in Fig. 5.10. The electrons collide with mercury molecules in the tube and as a result of collision ultraviolet light is emitted. The ultraviolet light excites the phosphor that leads to white light conversion. Large TV sets or monitors use CCFLs of 3 mm in diameter. However, recent movements on prohibition of the mercury which is a toxic material and recent development of high-efficacy pseudo-white LEDs boost the usage of the LEDs in the display BLUs.

5.1.10 Conclusions

A backlight is functioning 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 section.

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 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 an LGP that is featured by micro-reflector elements. The angular luminance can be squeezed by combining the light deflecting elements and light reflection micro-deflectors in a light-guide plate. A variety of light-shaping BLUs can be realized by selecting proper light reflector and deflector elements.

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

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