Abstract: Over the past decade, light-emitting diodes (LEDs) have been adopted for use in various liquid crystal display (LCD) devices, from mobile phones to LCD televisions. LCDs with LED backlight units have become a popular choice for display purposes. For LCD devices, the quality and features of the light source affect or even directly determine the optical quality and market competitiveness of the LCD products. Several advantages of LEDs solve a few outstanding problems with LCDs. LEDs inside LCDs have solidified the mainstream status of LCDs. We describe the types and structures of LED LCD backlight units, the market trends and technological developments, the advantages and key technologies of LED LCD televisions, and the key points in the optical design of LED backlights.

Key words: LED LCD backlight, LCD backlight, backlight unit, LED backlight.

19.1 Introduction
With the rapid increase of modern multimedia requirements, a wide range of display devices have become available. Thin-film-transistor liquid crystal displays (TFT-LCDs) are one of the most popular display devices. They range from small to large in devices such as mobile phones, notebooks and netbooks (NBs), car navigation systems and televisions. Because an LCD cannot radiate by itself, it has to rely on an external source to provide the illumination. Generally, a backlight unit (BLU) positioned on the back of an LCD cell is used to supply sufficient and uniform brightness and light for transmissive and transflective LCDs. Around 2004, LCD technology became suitable for televisions. Due to the strong market demand for thin flat-panel televisions and the limits on other display technology from technological bottlenecks, LCD televisions have gradually penetrated the television market. The penetration rate of LCD televisions exceeded 50% for the first time in 2008 and they have substantially replaced the cathode ray tube (CRT).

However, LCD televisions still have many shortcomings, such as poor viewing angles, response times, contrast ratios and color gamut compared to plasma televisions. Therefore some people have always thought that the LCD television would just be a transitional product, unless its shortcomings could be overcome or its features improved. Currently, everyone agrees that the LED light source has been the savior of LCD technology. LEDs can effectively overcome the shortcomings of LCDs and enhance their quality. Thus LCDs have successfully consolidated their mainstream status, especially in LCD televisions. The shipment proportion of LED and cold cathode fluorescent lamp (CCFL) LCD televisions based on a survey by Displaybank in February 2012 is shown in Figure 19.1. For LCD televisions, the LED penetration rate is increasing and
it exceeded 50% in the last quarter of 2011.

Fig.19.1 Shipment proportion of LED and CCFL LCD televisions.

Over the last decade, organic light-emitting diode (OLED) display technology has been the biggest threat to LCD technology. Although the LCD technology using LEDs has improved and can be further enhanced in the future, as long as the OLED display technology manufacturing costs decline, LCD technology is still in danger of being replaced by OLED technology. This is because OLEDs are self-emissive and have many other advantages over LED LCD technology, such as wider viewing angles, faster response times, slim body, light weight and they can flex.

19.2 Types of LED LCD backlighting units (BLUs)

19.2.1 Technical considerations for the light source
The most significant part of a BLU is the light source. The best light source for a specific BLU is determined by factors such as spectral content, luminous flux and efficiency, operating temperature range and stability over that range, and dimmability. The types of light source used in BLUs include: LEDs, CCFLs, hot cathode fluorescent lamps (HCFLs), external electrode fluorescent lamps (EEFLs), flat fluorescent lamps (FFLs) and electroluminescent (EL) devices. CCFLs were once considered the best light sources for LCDs, even though they have many shortcomings.

Table 19.1 General characteristics of light sources for BLUs
The advantageous properties of LEDs and FFLs make them more suitable than CCFLs for use in a BLU. Within the above categories, the main types of LEDs used include: side-view white LEDs, top-view white LEDs, RGB multi-chip LEDs and single-color LEDs.

19.2.2 BLU classification
In general, there are four LED BLU structures for LCDs differentiated by the position of the light source and by their structural characteristics: edge-type, direct-type, hollow-type and folded-mixin-light guide plate (LGP)-type. Schematic diagrams of each type are shown in Figures 19.2a–19.2d.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>CCFL</th>
<th>White LED</th>
<th>RGB LED</th>
<th>FFL</th>
<th>EEFL</th>
<th>HCFL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical efficiency (lm/W)</td>
<td>80</td>
<td>&gt;100</td>
<td>&gt;60</td>
<td>30</td>
<td>80</td>
<td>65</td>
</tr>
<tr>
<td>Color gamut (% of NTSC specification)</td>
<td>72–80%</td>
<td>&gt;65%</td>
<td>&gt;100%</td>
<td>80%</td>
<td>72%</td>
<td>92%</td>
</tr>
<tr>
<td>Mercury Produced heat</td>
<td>~4 mg</td>
<td>0 mg</td>
<td>0 mg</td>
<td>0 mg</td>
<td>&lt;4 mg</td>
<td>&gt;5 mg</td>
</tr>
<tr>
<td>Gas composition</td>
<td>Hg, Ar, Ne</td>
<td>None</td>
<td>None</td>
<td>Xe, Ar, Ne</td>
<td>Hg</td>
<td>Ar</td>
</tr>
</tbody>
</table>

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Edge-type structure
An edge-type structure has at least one LED light bar located at an edge of the LGP of the LCD device, as shown in Fig. 19.2 (a). Light is transmitted through a light guide by means of total internal reflection. The key components of an edge type structure include: LEDs, an LGP with a micro-structure or dots, a back reflector and diffusers. To meet the requirement for low power consumption, a brightness enhancement film (BEF) or dual brightness enhancement film (DBEF) needs to be used in the BLU.

![19.2a Schematic diagram of an edge-type backlight structure for LCDs.](image)

Direct-type structure
A direct-type structure has LEDs positioned below the LCD panel, as shown in Fig. 19.2(b). A typical direct-type backlight device includes: several LEDs placed above a metal core printed circuit board (MCPCB), a reflector, a diffusion plate and some optical function films. This structure has the advantages of a large backlight, high brightness and light weight and is also easier for local dimming. However, to maintain a uniform
brightness, a light-mixed cavity is necessary between the light sources and the diffusion plate. For this reason, a direct-type BLU is thicker than an edge-type BLU.

**19.2b Schematic diagram of a direct-type backlight structure for LCDs.**

**Hollow-type structure**

Hollow-type structures have two directional LED light bars located at the two edges of the hollow cavity of the BLU, as shown in Fig. 19.2(c). A hollow-type structure BLU is composed of at least two LED light bars, a hollow cavity, a patterned reflector placed at the bottom of the cavity, a structural diffusion plate and some optical films. The poor brightness uniformity is generally a serious drawback of this type.

**19.2c Schematic diagram of a hollow-type backlight structure for LCDs.**

**Folded-mixing-LGP-type structure**

A folded-mixing-LGP-type structure has at least one folded mixing color LGP and several multiple-color LEDs, typically RGB LEDs, positioned below the main LGP, as shown in Fig. 19.2(d). Its main components comprise: high-power multiple-color LEDs, a folded mixing LGP, a main LGP placed behind the LCD panel, a 90° coupling reflective mirror and a 180° coupling reflective mirror.
Philips Lumileds Lighting Company has presented a typical structure for a BLU assembly. This uses a Luxeon DCC as a light source, which is based on RGB LEDs with a Lambertian radiation pattern, as shown in Fig. 19.3 below. The multicolored light emitted from the multiple-color LEDs is coupled into the mixing light guide with a 90° mirror. This light is propagated, diffused and mixed in the mixing light guide. Uniform white light can be obtained from the folded mixing LGP. The 180° mirror then directs this white light into the main light guide. This type of structure has the advantages of high brightness, wider color gamut, compact shape and good thermal dissipation.

19.3 BLU assembly using a Luxeon DCC as a light source.\(^\text{12}\)

| Table 19.2 General characteristics of three materials used for LGPs |

19.3 Technical considerations for optical films and plates

The optical qualities of a BLU depend on the optical films or plates used, such as an LGP, a diffusion film, a prismatic BEF, a micro-lens BEF, a reflective polarizer BEF and a diffusion plate. LGPs are usually made of optical grade materials such as polymethyl-methacrylate (PMMA), ZEONOR® or polycarbonate (PC). Table 19.2 lists the general characteristics of these three materials. The materials used for LGPs in the current market are still based on PMMA. An LGP can be either wedge-shaped or flat. In general, because of space considerations, mobile phones, car satellite navigation devices, notebooks, and small and medium-sized products commonly use a wedge-shaped LGP such as that shown in Fig. 19.2(a).
Structured BEFs and reflective polarizer BEFs can recycle some of the wasted light energy, increasing the effective area of the luminance. The 3M Company manufactures BEFs, named the Vikuiti™ BEF II\textsuperscript{13} and BEF III,\textsuperscript{14} which can direct diffused light into the backlight and through the LCD. This increases the brightness for an on-axis viewer. Typically, two orthogonally aligned BEFs are used in the BLU of mobile products while the BLU of monitors and televisions uses a single BEF. In comparison, the Vikuiti™ DBEF, a very common reflective polarizer BEF, uses 3M’s multi-layer optical film technology.\textsuperscript{15} The DBEF increases the amount of light available for illuminating LCD displays by making use of light that would normally be absorbed by the rear polarizer of the LCD panel. The backlight efficiency is increased while maintaining the viewing angle. It can increase on-axis brightness by up to 60% in NB displays with a slab LGP and up to 97% in NB displays with a wedge LGP. The brightness gains of the Vikuiti™ BEF II and BEF III are listed in Table 19.3 below.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>PMMA</th>
<th>ZEONOR</th>
<th>PC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportion</td>
<td>1.2</td>
<td>1.01</td>
<td>1.20</td>
</tr>
<tr>
<td>Water absorption (%)</td>
<td>0.3</td>
<td>&lt;0.01</td>
<td>0.2</td>
</tr>
<tr>
<td>Transmittance at 3mm</td>
<td>92</td>
<td>92</td>
<td>88</td>
</tr>
<tr>
<td>Index of refraction</td>
<td>1.49</td>
<td>1.53</td>
<td>1.59</td>
</tr>
<tr>
<td>Hardness</td>
<td>2H</td>
<td>H</td>
<td>B</td>
</tr>
<tr>
<td>Glass transition temperature, $T_g$ (°C)</td>
<td>105</td>
<td>140</td>
<td>145</td>
</tr>
</tbody>
</table>

Table 19.3 Brightness gains of Vikuiti™ BEF II\textsuperscript{13} and BEF III\textsuperscript{14}

<table>
<thead>
<tr>
<th></th>
<th>Single sheet</th>
<th>Two sheets crossed at 90°</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEF II</td>
<td>60%</td>
<td>120%</td>
</tr>
<tr>
<td>BEF III</td>
<td>59%</td>
<td>111%</td>
</tr>
</tbody>
</table>

The main aim in the development of optical films and plates is multi-functional integration, to produce a so-called integrated optical film or plate. Examples area BEF with a diffusion function, a diffusion film with a brightness enhancement function (usually called a gain diffusion film) and an LGP with a diffusion and/or brightness enhancement function.

(Continued)

**Title-1**

19.4 Requirements for LCD BLUs

19.4.1 Features of LCD BLUs

An ideal BLU needs to have features such as good uniformity of the brightness, ultra-slim, light weight, ultra-narrow bezel, low power consumption, long life, wide color gamut (good white spectrum), short response time, large brightness adjustment range, fast modulation, temperature insensitivity, color that is adjustable according to the temperature, support for field sequential color technology, flexibility, support for two-dimensional (2D) and three-dimensional (3D) convertible displays, user friendly, environmentally friendly and low cost. Therefore, the light source itself should be slim, light and user and environmentally friendly and have low power consumption, a long life, quick response time, fast modulation, wide color gamut and a color adjustable according to temperature.

19.4.2 Environmental requirements

There are both legal environmental requirements and optional energy saving programs that can affect the development and use of electronic equipment. In July 2006, the European Union (EU)
began the formal implementation of the RoHS Directive: the restriction of the use of certain substances in electrical and electronic equipment that are potentially hazardous to us. One of these controlled substances is mercury. However, as there is an exclusion clause for it, CCFLs can still continue to use mercury for now.


Energy Star is an international standard for energy-saving consumer products and programs. The project was initiated in the United States in the 1990s and has become multi-national. Manufacturers can choose of their own accord to affix the Energy Star label to qualified products. The first products included in the project were mainly computers and other information appliances. It was then gradually extended to motors, office equipment, lighting, appliances and soon. Table 19.4 lists the calculations for the maximum power requirements in the on mode.\(^{16}\)

### Table 19.4 Calculation of maximum on mode power requirements (\(P_{\text{ON MAX}}\))\(^{16}\)

<table>
<thead>
<tr>
<th>Product type</th>
<th>(P_{\text{ON MAX}}) (watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>diagonal screen</td>
<td>(r) is the screen resolution in megapixels and (A) is the viewable screen area, rounded to the nearest 0.1 square inches</td>
</tr>
<tr>
<td>size, (d) (inches)</td>
<td></td>
</tr>
<tr>
<td>(d&lt;12.0)</td>
<td>((6.0 \times r) + (0.05 \times A) + 3.0)</td>
</tr>
<tr>
<td>(12.0&lt;d&lt;25.0)</td>
<td>((6.0 \times r) + (0.0145 \times A) + 4.0)</td>
</tr>
<tr>
<td>(25.0&lt;d&lt;30.0)</td>
<td>((6.0 \times r) + (0.18 \times A) - 40.0)</td>
</tr>
<tr>
<td>(30.0&lt;d&lt;60.0)</td>
<td>((0.27 \times A) + 8.0)</td>
</tr>
</tbody>
</table>

#### 19.5 Advantages and history of LED BLUs

19.5.1 Advantages of LEDs for LCD BLUs

LEDs provide numerous options and advantages for LCD BLUs. Generally the advantages of an LED BLU are the following.

**Low operating DC voltage**

LEDs use a low-voltage power-driven supply, unlike the high voltage power needed for a CCFL. Therefore, they do not need an inverter. This significantly helps to make an LED safer and reduces electronic noise. Not only that, an LED circuit can use less space, costs and energy consumption are reduced and the heat that would be generated by the inverter is not lost. The design of the power supply module is also relatively simple.

**Wide operating temperature range**

LEDs can work instantly at all temperatures without the need for heaters. The operating temperature range of an LED is between about −40 °C to +85 °C. LEDs can start promptly at −40 °C unlike CCFLs, which do not work properly in such environments. As LEDs are functional over a wide temperature range, they are favored by the military and in aviation, exploration and similar fields.

**High luminous efficiency (low power consumption)**
At present, the luminous efficiency of a white LED for use in a BLU is over about 130 lm/W. This is nearly twice as efficient as a CCFL. As LED technology progresses further, this luminous efficiency will continue to improve.

**Package size and chroma selection flexibility**
The optical design and use of LEDs is flexible. They are scalable and the chroma selection is flexible.

**Wide color gamut**
For the RGB LEDs used in LCDs, the National Television System Committee (NTSC) color gamut can be over 100% and can even achieve 150%.

**Longer operating life**
An LED has a specific lifespan. The lifetime is 60 000 to 100 000 hours, for a suitable current and voltage, which is far longer than a CCFL. Using LEDs can greatly extend the life of an LCD television and has overwhelming advantages compared with plasma technology.

**Rapid switching speed**
The response time of an LED is as short as a nanosecond, which is about one millionth that of a CCFL. The screen on an LCD device can appear blurry because of the slow response time of the liquid crystal. This is caused by screen persistence of fast moving objects. This drawback can be solved to some extent by using an LED BLU. An LED can support instant backlight blinking technology and dynamic scanning backlight technology. This technique effectively reduces motion blur and the display quality will be significantly improved. An LED can support the field sequential color technology. The color filter, which accounts for 30% of the cost of an LCD device, can be replaced by quick scanning RGB LEDs. An LED can also support local dimming technology. This technique can achieve high contrast and enhance the color saturation for low power consumption.

**Wide adjustment range for brightness, contrast and chromaticity**
LED power control is simple and the brightness adjustment range is large, unlike CCFLs, which have a threshold for the minimum brightness. Therefore, in the bright outdoors or dark indoors, it is simple for users to adjust the brightness of the display device for ease of viewing. This is particularly useful in automotive, avionic and marine electronics, where the product display must be able to deal with lighting conditions ranging from bright sunlight to the moon at night. In addition, when the video display source switches between computers and DVD players, it can be easily adjusted between a 9600 K and 6500 K white balance, without sacrificing the brightness and contrast.

**Environmentally friendly**
LEDs are made of non-toxic materials. Unlike incandescent lamps, they cause no mercury pollution, and there is no UV or IR radiation in their spectra.

**Quicker illumination to stable brightness**
LEDs require no warm-up time or general heating.

**Robustness**
LEDs have a high resistance to mechanical shock as they do not have glass tubes. LEDs are slim, light, safe and quiet: they are a solid-state solution without an inverter.

The above advantages significantly promote the use of LEDs in BLUs. Moreover, for specialized products such as military, avionics, marine and automotive displays, LCDs based on CCFLs are unable to meet user requirements. However, there are still challenges in using LEDs. In particular, these include cost, system design complexity and performance with temperature. For a high power
LED BLU, it is very difficult to use the edge-type structure with a narrow bezel and the direct-type with high brightness uniformity and slim body. For a high-power RGB LED model, the optical design makes it difficult to obtain good color control and high color uniformity. Some of the time there will be an uneven color because the decay rate of each one of the LED colors is inconsistent. The heat produced by the LED will lead to LED color variation, LED brightness variation, shortened lifetime, deformation and LGP aging.

19.5.2 Development history of LED BLUs

LED BLUs were first used in mobile phones. This application of LEDs was also the fastest to penetrate the market for LCD products. Since edge-type BLUs with a side-view-type white LED do not require much packaging or high operating power, they have proven to be the best choice. From about 2006, the market began to use LEDs in the BLUs of notebooks. In 2006, computer manufacturers produced only 11.3-inch and 12.1-inch notebooks using LEDs. At the beginning of 2007, several computer manufacturers launched a 13.3-inch and even a larger 15.4-inch product using an LED backlight. The most common choice is a wedge-shaped LGP with a white top-view-type LED bar.

The LED industry and LCD industry intended to use LEDs in televisions. An RGB LED BLU was first used by Sony Corporation in August 2004 for its 40-inch and 46-inch QUALIA 005 LCD televisions. The power consumption for the 40-inch and 46-inch models is 470 W and 550 W, respectively. To solve the problem of how hot these become, the models use fans, heat pipes and heat sinks. The heat pipes are horizontally arranged and there are large heat sinks on both sides of the back of the BLU. The heat passes through the heat pipes to the heat sinks on both sides, which are cooled by fans. Using this particular design, the color gamut can be extended up to 105%. This elaborate design is expensive and uses a thick backlight unit (up to 10 cm). South Korea’s Samsung Electronics demonstrated 46-inch and 40-inch LCD televisions without additional thermal design at the 2005 CES show. They used direct-type BLUs with a medium-power (0.3–0.5 W) LED and color sensor.

In 2006 there were crucial developments for LCD televisions. There were several technological advances and solutions to problems. Larger LCDs were successfully developed, such as LG Display’s 100-inch model and Samsung Electronics’ 82-inch model. A double frame rate (or higher) became possible, which can effectively solve the dynamic image blur. Local dimming (also known as high dynamic range) technology using an LED backlight can make the contrast quality up to 10 000 or more, and greatly reduce energy consumption. Further, eight-domain multi-domain vertical alignment (MVA) technology can reduce the color washout problem of the previous MVA technology, solving the problem of the LCD viewing angle.

The main focus of research for LCD LED BLUs is still to achieve high color saturation (or wide color gamut). Ultra-slim LCD televisions are realized by using a direct-type BLU with low-power LEDs or an edge-type BLU with medium power LEDs. The field sequential color method works without a color filter. It uses direct fast-switching R-, G- and B-LEDs to produce the respective R-, G- and B-display pictures, through the persistence of vision to create full-color display effects.

The first large-screen LCD television with an edge-type LED BLU, the KLV-40ZX1M, was launched by Sony in September 2008. It was Sony’s thinnest 40-inch LCD monitor measuring a mere 9.9 mm in width. However, it was expensive so demand for the product was poor. Samsung Electronics then launched a mid-priced LCD television with an edge-type BLU using medium-power LEDs. Due to a sales strategy highlighting the slim body, price and quality, Samsung Electronics successfully created the LED LCD television market. Thus, LED LCD televisions were a sought after commodity in 2009. Hence the market for LED LCD televisions was created.
According to a report by NPD DisplaySearch, due to lower-than-expected consumer adoption of LED LCD televisions at the end of 2011, television makers changed their strategy for direct-type LED BLU televisions by developing products that use less power and cost less by reducing the number of LEDs per television set. Their aim is to develop an adaptation of the original LED BLU with a slim design and better picture quality.

End Part 1

In the second and final installment, the author will begin with a short history of the market trends and technological developments which have driven the evolution of LED LCDs. This will be followed by an in-depth exploration of the optical design techniques used in today's state-of-the-art displays.

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