Chapter 3
Display Components

3.1 Backlights

Backlights are one category of transillumination (in addition to edge and wedge lighting) used to provide light to nonemissive displays. Display technologies where pixels serve only as light valves need some form of light by which the viewer can discriminate the image. This applies primarily to LCD technology. However, some LCD applications, such as military radios, are transflective and depend on ambient illumination for day use. But even in cases such as this, night-time use requires supplemental lighting that is built into the display backplane.

3.1.1 Cold- and hot-cathode fluorescent lamps

Fluorescent lamps were the earliest form of LCD backlighting, being largely replaced by LEDs beginning in the mid-1990s. Because there are military displays still using this technology, it is appropriate to discuss it here.

There are two forms of fluorescent lamp: hot cathode and cold cathode. Hot cathode provides a higher-intensity electron source and is typically used to address high-sunlight day-mode lamp operation, while cold cathode is used for dark ambient night-mode conditions. Fluorescent lamps offer high efficiency and ideal form factors (i.e., they can accommodate nearly any size display); however, dimming circuitry to achieve graduated light levels from maximum luminance (200 fL or higher) down to minimum luminance (as low as 0.01 fL) requires complicated drive schemes that can account for as much as 60% of the overall display cost. Furthermore, maintaining flicker-free lamp performance at very low drive levels (i.e., 0.5 fL or lower) can be challenging. In addition, for applications where a display must be night-vision compatible, MIL-L-85762A specifies NVIS radiance units as low as 2.2×10^{-9} for white and 1.1×10^{-8} for colors. The difficulty in meeting NVIS-A requirements is that virtually no red emission is allowed, but even NVIS-B and -C compatibility poses challenges in terms of maintaining luminance and color balance without compromising NVIS radiance. Some backlight schemes (e.g., one introduced by Kaiser circa 1996) use a decoupling scheme where two lamps are employed, one for day and one for night, with the hot-cathode day lamp being disabled when the night lamp is used. The night lamp must nevertheless employ a thin-film reflective (interference) filter to suppress infrared emissions. In addition, both lamps are driven by a common dimmer circuitry with appropriate switching elements, heaters for rapid warm-up, and temperature and luminance sensors as part of a feedback loop for maintaining optimum temperature and desired brightness level.[40] Because cold-cathode lamps are especially sensitive to environmental temperature, military systems employing them must always use heaters.

Lamp designs have either been serpentine in nature or an array of straight tubes; some designs have no tubes at all but are flat-type lamps. Flat lamps are meant to alleviate some of the issues with bulb-type lamps, for example light uniformity and directionality. For bulb-type lamps, uniformity has been an underlying problem due to the necessary spacing between bulb patterns, requiring a diffuser in front of the lamp. Further, because fluorescent bulbs emit in all directions (not necessarily toward the display), a reflector behind the lamp is necessary.

The structure of a standard low-pressure backlight fluorescent lamp is seen in Fig. 3.1. The lamp is composed of glass quartz tubing, coated on the inside with an RGB triphosphor material (zinc silicate and halophosphates). The fill gas is a mixture of neon, argon (Penning mixture as with gas plasma), and mercury vapor. When a relatively high (90 to 250 V) AC voltage is applied between the electrodes, the gas emits ultraviolet photons (primarily at 253.7 nm, and to a lesser extent at 185 nm) that bombard the phosphor and emit visible light in the 380- to 780-nm region. The getter (applied to the cathode in Fig. 3.1) is a coating of barium (or alternately aluminum, magnesium, strontium, etc.) that can react with and/or absorb spurious gas molecules to maintain or increase internal vacuum. Cold-cathode fluorescent lamps have long operating lives (the time period required to reach 50% light output) between 25,000 to 50,000 h, and brightness between 2000 to 5000 cd/m^2 (depending on the technology). Radiation damage to the phosphor is the typical breakdown mechanism. In addition to phosphor damage, visible light output is further degraded through mercury deposition on the phosphor and glass (seen by a darkening of the tube wall).

Hot-cathode fluorescent tubes are similar to CRTs in that electrons are excited via thermionic emission (a heated filament that can either be the cathode itself or a separate, electrically insulated heater). Hot-cathode lamps are generally better suited for backlights where high efficiency, high luminance, and wide dimming ranges are critical. At power densities of less than 100 mW/cm^2, and with protective coatings on the phosphors, useful lamp life can be attained that approaches 20,000 h. Hot-cathode electrodes can be operated at lower

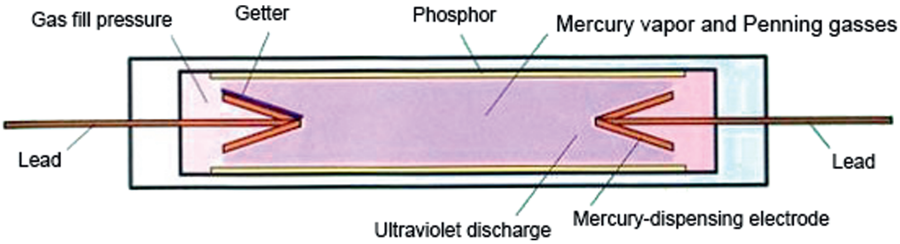

Figure 3.1 Basic diagram of a fluorescent lamp (figure origin unknown).

voltages, typically on the order of 15 V, but tend to have greater efficiency at higher operating currents compared to cold-cathode electrode lamps. Because the electrodes consume power but no light, lower operating voltages allow efficiencies as high as 75 lm/W, providing luminous output of 5000 fL or greater, as measured at the output of the backlight diffuser, with dimming ranges of more than 2000:1.[*] Heating allows the cathode to provide much higher power density than cold cathodes; i.e., hot cathodes provide a significantly greater number of electrons per unit time, per unit cathode surface area. After initial lamp ignition, electron flow in the arc discharge increases until it is limited by an external circuit ballast function, e.g., inductive circuit elements and pulse-width modulation. Figure 3.2 provides a schematic of the hot-cathode lamp. Note that the discharge that occurs is basically the same phenomenon that occurs with cold-cathode operation.

3.1.2 Light-emitting diode backlights

Aside from their use as direct-view displays, LEDs have made substantial progress as a backlight technology, starting with their introduction in 1993. By 2004, gallium-nitride (GaN) white LEDs were already demonstrating luminous efficiencies equivalent to triphosphor fluorescent lamps, and by 2008 efficiency had nearly doubled, not only in terms of efficacy, but also in terms of continuous drive current, thermal properties, and cost as well. Continual improvement in LED backlights has created a fundamental shift in supporting technology options for avionics-grade AMLCDs.

Rockwell Collins took an early manufacturing lead in LED backlights, introducing as many as five generations in 12 years, beginning in 1999. At the lowest drive currents, e.g., 5 to 10 mA, early devices achieved 42 to 47 lm/W

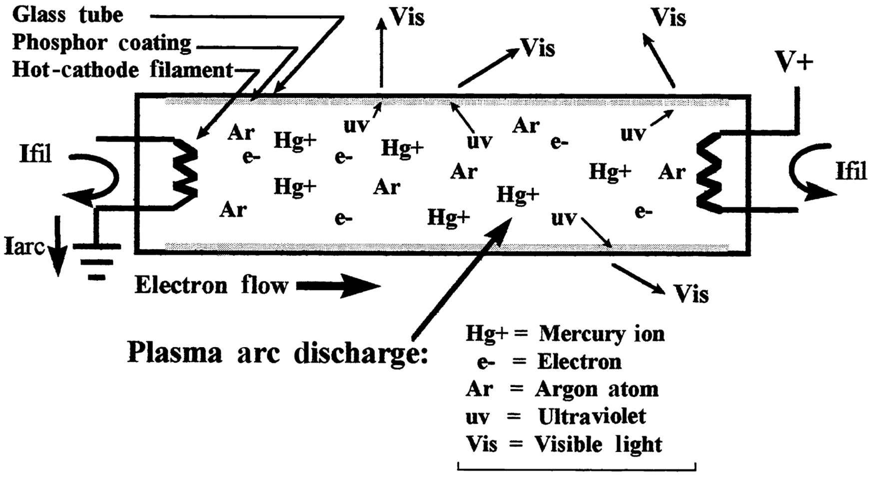

Figure 3.2 Hot-cathode lamp schematic.[41]

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[*] Although hot-cathode electrodes consume no light, their glow can sometimes be seen when the lamp is operated at very low luminance levels. This is particularly true for cases where the placement of the backlight in the reflective cavity and the reflector cavity/diffuser design are not optimized for low-luminance operation.

(generations 1 and 2), while later devices achieved 70 to 90 lm/W (generations 3.5 and 4) at minimum continuous drive currents of approximately 30 mA. Maximum drive currents reached a peak of 650 mA (generation 3.5). Practical limits for avionic display products dictated a reversal in this trend, to where maximum drive currents were progressively reduced to approximately 150 mA for the latest LED backlight introduced in 2010 (generation 5), with efficiencies close to 250 lm/W.

High-reliability LED backlighting requires attention to thermal management, and early white emitters had challenging limitations associated with mechanical device integrity. Rockwell Collins' generation-1 and -2 devices were limited to about 100 °C maximum junction temperature (a fairly low limit for avionics). Generation-3.5 devices achieved junction temperatures of 150 °C, while later devices regressed from this trend. All the while, starting with generation 3 in 2003, improvements were afoot to improve long-life passive cooling techniques, i.e., LEDs more efficient in shedding heat (thermal resistance), to where thermal resistances that were typically 500 °C/W were now only 70 °C/W or less. Improvements in maximum junction temperature combined with reduced thermal resistance (a greater heat-shedding ability) allowed greater tolerance to printed wiring-board ambient temperatures, thus improving backlight performance, life, and reliability.

Emitter depopulation for LED backlights became a significant advancement in the evolution of avionics display backlights. While typical emitter densities of 20 LEDs per square inch were true of backlights in the late 1990s (Rockwell Collins'generation 1), by 2010 this was effectively reduced to only two LEDs per square inch (generation 5), thus reducing LEDs to display area ratios on the order of 23.5 to 1.9%. Typical backlight cavity depths (the offset distance between the LED emitter and the LCD light-valve plane) increased with diminishing emitter densities from 0.7 in. (generation 1) to 1.5 in. (generation 5) to increase light-valve coverage per LED. Individual emitter component cost reductions on the order of 20:1 coupled with greater efficiencies leading to a reduction in LED emitters per backlight helped to improve LED cost competitiveness with fluorescent backlight technology. Figures 3.3 and 3.4 show two generations of Rockwell Collins LED backlights, demonstrating the marked reduction in LED emitters.

As of this writing, the question of using organic light-emitting diodes for backlights is still premature, given their relative expense, complexity, and issues regarding life and brightness. If OLEDs ever become contenders for military display backlights, the more likely scenario would be to use them as primary

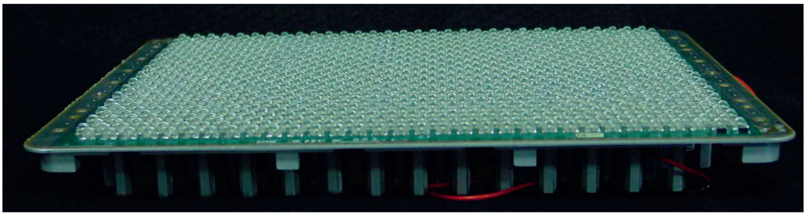

Figure 3.3 Rockwell Collins generation-1 LED backlight (1999 to 2000).[42]

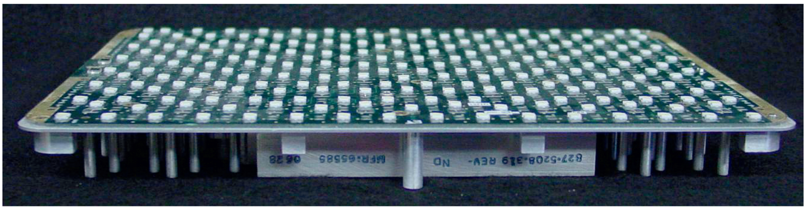

Figure 3.4 Rockwell Collins generation-3 LED backlight (2003 to 2007).[42]

display engines. Except for mass-market cell phones, digital still cameras, and personal-digital-assistant devices, there are no manufacturers that have yet gone to market with a direct-view OLED avionics display, let alone an OLED backlight. While the military market may eventually see the introduction of direct-view OLED displays, the advent of OLED backlights is less likely.[43,44]

3.2 Polarizers

Polarizers are an important element in display applications, especially when manipulation of light according to a unique electric-field (E-field) vector is required, such as with LCDs. The essence of an ideal polarizer is to pass only that E-field component that aligns with the polarizing axis of the polarizer, blocking the component that is perpendicular. This is the basis for linear polarization, although there are other forms of polarization, such as circular and elliptical, that depend on further manipulations. In explaining polarization, it is perhaps useful to first point out that for microwaves, parallel conducting wires can serve as a polarizer and will pass waves with E-fields perpendicular to the wires, but not those with E-fields parallel to the wires. This tells us that any material possessing molecular lattices where electrons can be set in motion in a direction aligned with the light ray's E-field will *absorb* the energy of that E-field rather than propagate it. By contrast, if electrons cannot be set in motion, or only minimally, there is little or no absorption, and the light ray propagates essentially undiminished.

The most common polarizing filter is a material known as Polaroid®, a material first developed in 1928 by Edwin H. Land. Early Polaroid was based on an assemblage of needle-like dichroic crystals of herapathite (iodoquinine sulfate) oriented in parallel and embedded in a plastic matrix enclosed between two transparent plates. A later Polaroid, called the H-sheet (1938), consisted of long molecules of polyvinyl alcohol (PVA) given a preferred direction through mechanical stretching, laminated to a support sheet of cellulose acetate butyrate. The PVA was stained with an ink containing iodine that caused the sheet to exhibit dichroism (see Section 2.2.1).

Naturally occurring sunlight, as well as artificial light propagating from a test lamp or display backlight, is made up of innumerable light rays, each with its own specific E-field oriented orthogonal to the direction of propagation.[†] Any one

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[†] There is also an associated magnetic field; however, the most common manifestations of radiation, whether visible or otherwise, are due to an E-field force and not a magnetic field force.

ray has a specific E-field orientation, but taken as a whole, the combination of E-fields is random, with uniform distribution throughout the plane orthogonal to the direction of propagation. One can resolve these random multitudinous E-fields into two primary field vectors: $\mathbf{E}_x$ and $\mathbf{E}_y$, representing the E-field components in the x and y axes, assuming a propagation direction along the z axis. Any linear polarizer, such as Polaroid, will absorb those parts of a ray's $\mathbf{E}_x$ and $\mathbf{E}_y$ components that coincide with the polarizer's optical axis, i.e., the axis along which the polarizer's constituent molecules are oriented. For a polarizer with its optical axis exactly aligned with the E-field of a given light ray, all of the E-field energy from that ray is absorbed (through excitation of electrons free to move along that axis). For a polarizer with its optical axis 90-deg orthogonal to the E-field of a given light ray, no electric field energy from that ray is absorbed (there is no electron excitation), and the ray is transmitted. For a polarizer with its optical axis at any other angle relative to the E-field of an incident ray, there is partial transmission and partial absorption. Figure 3.5 provides a pictorial understanding of the scenario described. For this figure, assume that the random E-fields of incident light rays are in the xy plane, traveling along the z axis, and that the x axis is both the horizontal axis and the molecular axis of the polarizer. The polarizing axis is in the vertical y axis, orthogonal to the molecular axis. Note that there is absorption of the E-field even when it is aligned with the polarizing axis. In practice, there is some attenuation (as much as 20%) due to a limited ability for transverse movement on the part of lattice electrons, while only 1% or less transmission is possible for waves with E-fields perpendicular to the polarization axis.

In Section 2.2 we examined a case where two such polarizers were placed on either side of an intervening LCD material. The first polarizer acts as a discriminator, passing only light with an E-field aligned with the polarization axis of the polarizer. This light is then channeled by the LCD molecules which, under the influence of an imposed E-field, conduct the light such that the E-field orientation can be altered anywhere between 0 and 90 deg. If the second polarizer (also known as the analyzer) is oriented with its polarizing axis 90 deg relative to the first polarizer, one can regulate the amount of light exiting the second polarizer according to Malus' law (recall that $I = I_{max} \cos^2 \theta$, where I_{max} is the amount of light reaching the second polarizer, and θ is the angular difference between the E-field vector of the light reaching the second polarizer and the polarizer's polarization axis).

3.2.1 Circular and elliptical polarizers

To understand how light can become circularly or elliptically polarized, we must consider at least two simultaneous light rays having the same direction of travel along the z axis, but with E-fields in the x and y axis that are perpendicular. If in phase, the two rays superimpose to produce a resultant field vector oriented at ±45 deg within the xy plane (the resultant amplitude of the wave is also larger by a factor of 1.41 than either component wave). Now suppose one ray's E-field waveform is shifted 90 deg relative to the other. The resultant E-field vector is no