Competing Display Technologies for the Best Image Performance.

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Abstract

Cathode Ray Tubes (CRT) has been the dominant display technology for years with its best image performance and low cost. During the last years the Flat Panel Display technologies, such as Liquid Crystal Displays (LCD's), started to replace the CRT mainly for its favorable form factor. Today the LCD image performance equalized the CRT and the attractive flat display products became such affordable that they pushed the CRT from its dominating market position and obtained the largest market share in value.

In the past, CRT set the targets for the digital imaging technologies, but today, modern image capturing, storage, transport, signal processing, and printing technologies have grown to such high levels that they demand for better display technologies and standards. At present, LCD being at the forefront of this display technology evolution, this key note address will focus on the latest image quality improvements in LCD and review alternatives like PDP and Projection. Special attention will be given to the latest developments and possibilities in Wide Color Gamut technologies and methods to reproduce accurate colors within a display device.

Introduction

In the 1970's the first LCD displays were commercialized as tiny, few characters displays for applications like digital watches and pocket calculators. Priced above 1000 US$, these products were only affordable for the rich.

Bulky CRT's were used for the televisions and most households owned one color television set placed in the living room and used for the daily watching to one of the few available TV channels.

In the early 80's the battle for the flat panel technology started. Scientists were dreaming about large sized, flat TV's, but there were many technology hurdles to be solved.

Display Effect, Black & White; Color

The 90^o TN (Twisted Nematic) LCD effect [1] is mostly used because of its independency of the optical characteristics from the LC layer thickness, enabling simple LCD manufacturing processes. In the early 80's the first Portable Computers, using passive matrix driven STN (Super Twisted Nematic) LCD [2] screens appeared on the market. The just invented STN effect had a much steeper transmission voltage characteristic than the TN effect which is a requirement to produce passive matrix driven LCD displays having high resolution and high contrast [3]. The STN effect is however an interference based effect, not capable to fully absorb the complete visible spectrum simultaneously and for this reason limited to an Yellow-Black or Blue-White operating mode. It was however sufficient at that time since the early computer displays were only monochromatic and it was even disputed whether color displays would ever be a requirement for computer use.

Another application that started in the early 80's was full color, pocket televisions. Color was obtained using the Black and White switching TN effect while applying Red, Green and Blue color filters on each pixel and backlighting the display with small fluorescent tubes. High contrast was achieved by applying Active Matrix Addressing [4, 5]. A matrix of Thin Film Transistors (TFT's) with each TFT connected to a corresponding pixel-electrode to charge and keeping charged the related LC pixel capacitor.

Mid 80's the battle towards larger screen sizes started. For the STN displays optical compensation technologies, such as LC compensation cells or optical compensation films, were introduced to obtain Black & White switching modes [6, 7]. Together with RGB color filters and time-multiplexed generated grey shades [8], full color images on STN displays became possible.
For the TFT displays the production yield (pixel defects due to failing transistors) were gradually improved. Today active matrix addressing has been matured towards the large (>40") TFT based LCD televisions with zero pixel defect guarantee as can be found in the shop today; while the STN displays are only left for the lower priced mobile phones and alike products.

Many display solution exist [9] but we focus in this paper on the ones which have most impact on the market today.

Resolution

CRT's are only capable to show high resolution images at limited electron beam currents and as such at limited brightness. For convenient viewing, high resolution CRT monitors require dimmed rooms with special treatments to prevent light reflections at the front glass.

With LCD technology, resolution and brightness are decoupled. The resolution is determined by the pixel count and structure, while the brightness can easily be increased within the backlight system. LCD technology brings the best resolution of all existing display technologies. LCD's do not offer only the largest amount of pixels, but also have the smallest gaps between the pixels, which are visible as a grid structure over the image. LCD panels are therefore favorable for close viewing applications, such as PC monitor's and portable computer displays.

In Projection systems, the resolution is mainly determined by the projection panel and the quality of the projection optics (which may go with high cost penalties). Most projection systems have XGA resolution (1024 x 768 pixels) or an equivalent in wide screen format.

Today, the WUXGA (1920x1200 pixels) is the highest resolution standard that is widely supported with technical solutions; while Ultra High Resolution LCD's like QUXGA (3840x2400 pixels) have already been mass produced.

The pixel count that needs to be addressed in a display is dependent on the method of color reproduction. LCD's in WUXGA format have one set pixels for each primary color; total 3 times 1920*1200 addressable pixels.

Contrast & Brightness

Long time, the flat panel technology lacked contrast compared to the CRT. Where the CRT originally set a challenging target for the daylight contrast of 100:1, today the LCD, PDP and Projection products have perfect black with contrast levels over thousands to one. The specified contrast values have became more a battlefield for the highest measurable numbers than a sensible number for performance comparison.

The brightness of CRT TV's is normally limited at around 100 nit for a full white screen, however the CRT is able to boost the power in small white area's and such way can generate a 5 times higher peak brightness's leading to sparkling images.

The LCD contrast has for a long time been limited below 100:1, resulting into 5 nit black level for a 500 nit brightness display; far too high for a good black level and limiting the available color gamut at the darker levels. For these reasons the brightness of LCD's was kept rather low, but now the contrast of the LCD has been improved dramatically, LCD's with 500 nit brightness are developed having small area brightness levels comparable to the CRT.

One of the latest development is dynamic backlight control [11, 12]. The light intensity of the backlight unit is dependent on the image content. At the moment an image has not the maximum brightness, the intensity of the backlight unit is reduced while simultaneously the signal towards the LCD panel is magnified. If the black level in the signal to the LCD panel is kept at the original value, the black level in the final image is reduced. Dynamic LCD backlight control increases the LCD contrast, the available color gamut at darker images and improves the viewing angle. Many algorithms are under development to generate the most optimum image qualities while simultaneously the average power consumption is reduced.

Grey Levels

Correct grey levels are very important to obtain good color reproductions. LCD's have however different optical response characteristic than CRT's and the LCD characteristics are even quite different for Red, Green and Blue light.

Historically, the signals to a CRT were standardized such way that the CRT electro optical response was compensated. Modern flat displays require a "gamma" response compensation to make the product behave similar than a CRT.

Graphic designers observe many difficulties with display products having wrong optical characteristics. They like to have excellent color responses, and as such correct grey levels for all colors. This has result to many PC based Color management solutions as often discussed on conferences like this one.

For PDP panels the grey shade reproduction is also difficult. Like DLP projectors, PDP displays are time sequentially addressed with binary subfields of pulses towards the pixels in the display [20, 21]. The number of grey scales in plasma panels is usually insufficient for human visual characteristics. Spatial and temporal dithering is applied to increase the number of grey levels, however also causes many artifacts in moving images, visible as some noise at the boundaries of the moving objects.

LCD projectors have the highest amount of problems with grey scale reproduction. Common LCD projectors consist of 3 panels, one for each primary color. Light to and from the LCD's are split and recombined using dichroic mirrors. The spectral characteristics of dichroic mirrors have however strong angular dependencies, causing visible color stains over the image. Next large temperature deviations over the LCD's occur which are changing during the heating up of the projector and causing spatial differences of the electro-optical characteristics. Lowest cost is obtained by allowing a large amounts of these unwanted effects and to minimize their visibility using electronic compensation circuitry.

Moving Artifacts

Recently there are many advances in improving the moving image artifacts of flat panel displays. The slow response speed of LCD's has been an annoying drawback for years, especially for applications with moving video, web browsing and scrolling.

Today, the LCD switching speed has been improved dramatically by applying new liquid crystal materials having lower viscosity and a larger dielectric anisotropy.

Unfortunately, like contrast, the LCD industry is also using the LCD switching speed as a battlefield towards best specified values and the specified numbers are becoming meaningless. Lower numbers are obtained by adapting the measurement method. The fastest response time that can be found for any grey to grey level transition is specified.

Next, very short switching times do not solve the LCD's sample and hold effects. Other methods to improve flat panel moving artifacts are required and are under development:

- LCD overdrive technology, where the voltages towards the LCD are pre-corrected for the changing LC behavior during switching [13].
- Higher image refresh rates, towards 120 Hz, such that the LCD capacitors are charged more frequently, preferably combined with motion estimation [14, 22].
- Black field insertion, such that the LCD images become "blinking" by writing black fields towards the LCD between the individual image fields [15].
- Scrolling Backlight, having a similar effect as black field insertion, however achieved with an easier drive scheme and without the light loss as occurs with black field insertion [16].

Factories

Figures 1 and 2 are overviews of the most important installed and planned flat panel manufacturing lines.

The flat panel industry has been moved from small Gen 1 glass substrates (Gen1: 320x400 mm^2) towards Gen 7 (Gen7: 2160x2460 mm^2 glass substrates) that can carry 12 pieces of 30"-wide panels simultaneously. Each LCD line has been build and optimized having a particular panel size in mind. The suppliers carefully distribute the different panel loads over their available lines to achieve the most economical panel cut from the mother glass plates; and as such to achieve lowest manufacturing costs.

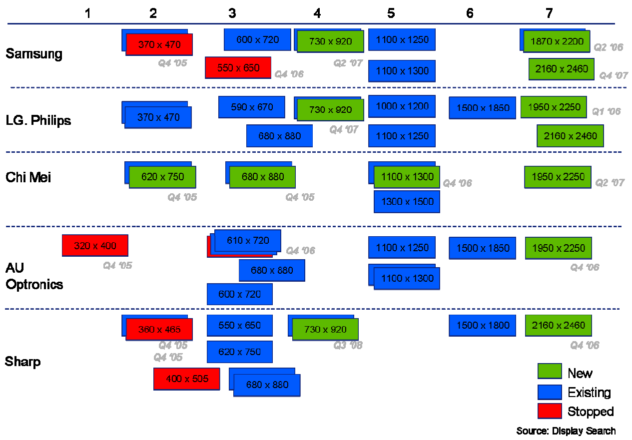


Figure 1: LCD Fab. outlook and expansion.

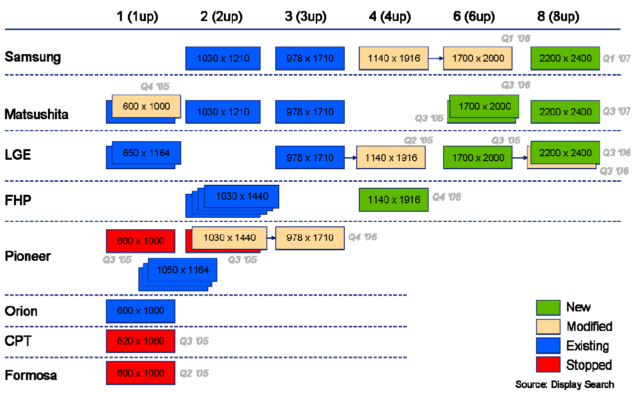


Figure 2: PDP Fab. outlook and expansion.

Cost & Market

Compared to PDP and Projection the LCD has highest cost; but it became sufficiently low to make the LCD the dominating technology in market value. At largest sizes, Rear Projection TV is lowest cost, however they are heavily under attack by the large PDP panels. At the smaller screen sizes, the CRT has lowest cost but the bulky and heavy tubes are nowadays abandoned from the offices and houses. Below 40" people prefer LCD technology for their Television or PC monitors.

New large sized multimedia applications will evolutes like Digital Photo Frames, VOIP devices, Electronic Virtual Windows and more. These new products will grow the number of screens per household and consequently result to further cost reductions.

The backlight unit of an LCD has relatively highest cost. The latest developments to reduce the cost of an backlight are higher LCD apertures and fewer fluorescent lamps in the backlight unit.

Display Color Standards and Typical Gamut's

Figure 3 shows the typical surface colors as can be observed under natural illumination conditions. The NTSC Color Gamut was originally intended to match the phosphors used in the CRT tubes, however due to improvements in CRT technology the phosphor materials were changed and the NTSC gamut became obsolete. The EBU and sRGB standards are today the most relevant ones

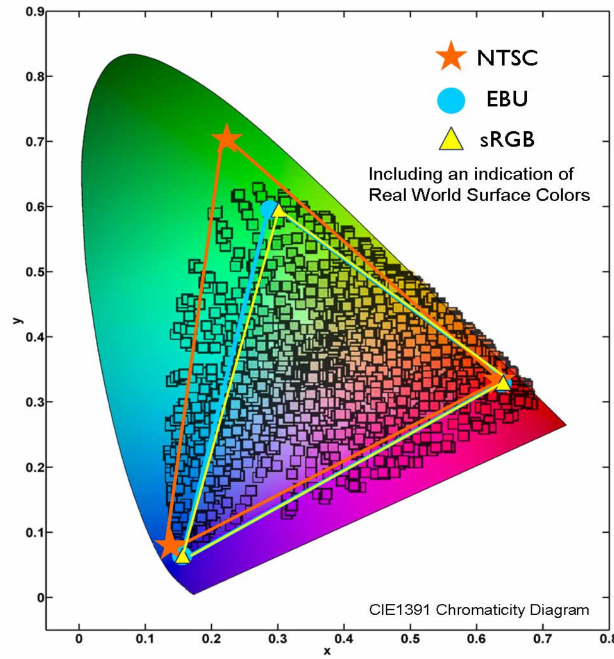


Figure 3: Color Gamut of typical Real-World Surface Colors compared to the NTSC standard (obsolete), the EBU and the sRGB standards.

Television signals had strong bandwith limitation and the storage-capacity for digital image material was rather poor. Next compromises had to be made between cost, image performance (brightness, gamut etc) and product life time. For these reasons the EBU color gamut was selected, which does not cover all the Real World Surface Colors, and led to the existing display solutions.

Today this situation is changing. The capacity for electronic data storage is rapidly increasing while the distribution of television signal has been improved dramatically with compression algorithms and broadband internet streaming technologies. New digital imaging technologies, like digital still camera's and digital camcorders, enable capturing and storage of wide color gamut images at consumer levels, including digital photo editing and high quality digital photo printing.

These developments generate new requirement for display solutions and standards like a wider color gamut, color gamut mapping algorithms, improved color accuracy, and more.

Advances in LCD color reproduction

Wide Color Gamut Displays.

The display community specifies the color gamut of a display as its percentage of the NTSC gamut within the CIE 1931 chromaticity diagram (resulting to less meaningful numbers).
Standard LCD panels have a color gamut close to sRGB (72% NTSC) and, due to a required UV filter between the backlight and the polarizer, an insufficient saturated blue primary (shifted towards too high y values).

There are a number of solutions to increase the color gamut, which basically can be split into 2 groups:

- **3 primary solutions:**
  At least one of the primaries is made more saturated by:
  - Applying narrower color filters
  - Use solid state light sources, such as LED or lasers
  - New lamp phosphors
- **Multiple Primary colors:**
  At least one Yellow, Cyan or Purple color filter is added such that the color gamut becomes quadrangle, Pentagon or hexagon.

Combined with new possibilities for color display architectures a number of promising opportunities are found.

A. Narrower color filters.

This is the most straightforward solution to expand the LCD color gamut; however due to the higher light absorption in the color filters the system efficiency degrades. To compensate the number of lamps in the backlight needs to be increased and higher power consumption is required. Results are increased system cost, increased heat problems, shorter panel life time and higher costs of operation. When optimizing the existing LCD generation the 72% NTSC gamut was already found to be the most attractive compromise to market.

B. LED backlight unit [17].

Strongly pushed by the manufacturers of high power LED's and by future expectations for solid state lighting, most LCD manufacturers have developed several LED backlight LCD prototypes and products.
The main advantages are the narrow and saturated emission spectra from the LED's. When selecting color filters that match the LED spectra high system efficiency and a very wide color gamut (>105% NTSC) can be achieved. Normally the blue primary is not improved compared to the standard (72%) NTSC panels.

The LED backlit technology is far from mature and is facing many technical difficulties:

- There is wide spread in the emission spectra from the LED's and it is required to select the LED's during the manufacturing process to obtain sufficient homogeneity.
- To obtain sufficient light mixing between the individual LED's the backlight unit needs to be thicker.
- Due to a relatively lower efficacy of the LED's, the required power consumption is increased.
- There are large thermal problems
- The LED's characteristics are unstable and drift with temperature and operating time [18]. Intelligent drive electronics with optical feedback and the tracing of the history of the LED's (operating time and temperature) is required to compensate for changing LED behavior.
- The manufacturing cost is approximately 3 times the CCFL solutions. The Cost of a 32" LED backlight unit alone is around US$ 400,-.

An advantage might be found to combine LED backlights with 2D dynamic backlight dimming [19] which further enhances the image quality and reduces average power consumption.

C. New lamp phosphors.

Promising and low cost solutions are the application of new Red and Green phosphors within the fluorescent lamps, which supply more saturated emission spectra; and match new color filters with these new emission spectra.
Several LCD manufacturers have already introduced such type of products (having 92% NTSC gamut) and it will become a mainstream technology for the higher end LCD panels soon.

D. Multiple Primary Color Projection Systems

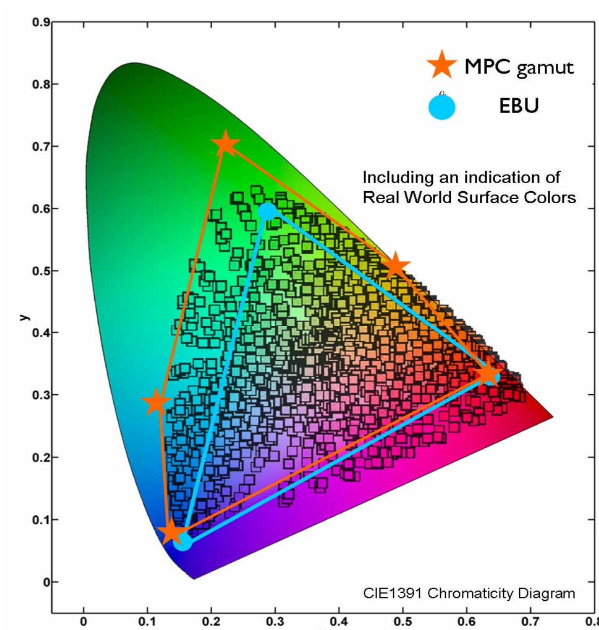


Figure 4: Wide Color Gamut using 5 primary colors.

Single panel DLP projectors make use of a RGB colorwheel to generate time-sequential colors. The colorwheel, located between the lightsource and the panel, is flashing the DLP panel with Red, Green and Blue light. MPC technology is introduced by adding new color filters to the colorwheel [23, 24].
The MPC technology allows for a wide range of new possibilities.

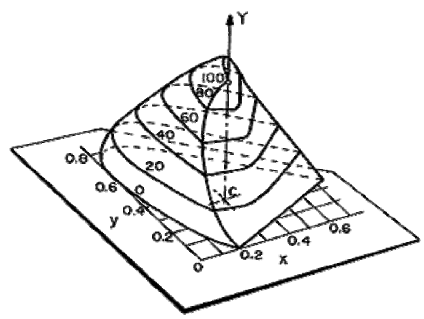
- **Wider Gamut.**
  By adding a Yellow and Cyan filter, the Gamut can be extended to areas where many out of EBU colors exist (fig 4).

- **Increased Brightness**.
  When we assume that the Red, Green and Blue filters each have 33% color efficiency; and the Yellow and Cyan filters will have 66%; an RGB colorwheel will have 33% efficiency and a RGBYC will have 46%. A brightness increase of 40% when moving from a RGB to a RGBYC colorwheel! Alternatively a standard color gamut can be taken where the MPC technology is used to increase the system efficiency. Note that a higher efficiency of a projector can be used to further miniaturize the projection panels and optics which will reduce the cost of the projection system.

- **Reduced color breakup.**
  Another advantage is the reduction of Color Break Up [25]. The addition of the Yellow and Cyan primaries changes the frequency and phases of the light-flashes into the human eye and MPC reduces the visibility of the Color Break Up.

Due to the advantages mentioned above, most single panel DLP products nowadays contain a multiple primary colorwheel.

Brightness Requirements
Another interesting aspect of the multiple primary color system is the match with brightness requirements. Figure 5 shows the



maximum brightness that a colored object might reach under natural light conditions.
Figure 5: Maximum brightness values for a colored object under natural light conditions.

The extremist coordinates on the locus can only be obtained when most wavelengths from the light are absorbed and as such the brightness shall than be very low. A display system with 5 primary colors generates a much better match with the volume of figure 3 than the conventional 3 primary color ones. Simultaneously it means that more of the available bit combinations generate valid color coordinates that coincidence within the volume of figure 5.

E. Direct View LCD; Multiple Primary Color Filter Pattern

Like in single panel projection systems, adding Yellow, Cyan or Purple color filters to a direct view LCD will increase the color gamut and/or the system efficiency [26 - 28]. When the number of addressable pixels (# TFT's) in the LCD is kept identical, the move to 5 primary colors will reduce the pixel count of Red, Green and Blue pixels from 33% to only 20%. The resolution and brightness of saturated Red, green and Blue objects are degraded, but the numbers of combination to generate white pixels are drastically increased; enabling new options for improved pixel layouts [29].

F. Direct View LCD; Multiple Primary Color Sequential

Recently the switching times of LCD panels have been improved dramatically and first prototypes of Color Sequential LCD's have been reported and/or demonstrated [30 - 33]. The LCD uses 2 different types of lamps that alternately illuminate the panel. In combination with the color filter pattern, the first lamp makes a first set of color primaries while a second set of primaries is obtained in combination with the second lamp. Alternative systems might contain only 2 types of color filters (4 primaries) with higher brightness and wider gamut (>100% NTSC).

New Color Video Standards

There are a number of new standards and modifications that are relevant to mention:

1. **The xvYCC standard (approved) [33, 34].**
   The xvYCC standard is derived from the YCC encoding and can transfer a wider gamut color space. The primary colors and reference white are identical to the sRGB standard. The new xvYCC standard clearly defines some available regions that were left undefined in YCC (the bit values 1 till 16 and 240 till 254) which values can be stored on DVD's in MPEG formats.
   The optic-electronic transfer curve as defined by the xvYCC standard extends above 1 and below 0 in the electronic signal. The display system needs to carry the negative values in the xvYCC RGB signal until the color space conversion.
   In Oct 2005 the xvYCC standard is included in MPEG [36] and on 22 June 2006 also in the HDMI version 1.3 [35].

2. **The XYZ standard (approved) [35]**
   The Digital Cinema Initiatives LLC decided to develop a standard for Digital Cinema and to embody a device independent color encoding within the Digital Cinema Distribution Master (DCDM). It is decided that the DCDM shall use the CIE1931 system of colorimetric (x y coordinates) to describe the color primaries X, Y, Z.

Display Calibration.

Today's HW and SW applications can define and manipulate colors with a palette of billions of colors. When the colors have to be sent to the display then the billions of colors need to be squeezed into the 8 bits/color requirements of the DVI connection and the display will receive a maximum of 256 x 256 x 256 = 16.7 million colors. If adaptations to the displays are performed at the PC side (e.g. Calibration), the colors transferred are reduced in numbers. To keep the maximum possible numbers, the monitor needs to simulate an ideal monitor from the wished standard. Therefore it is preferred to load the coefficients derived from a calibration directly into the LUT's (Lookup Tables) in the monitor.

Conclusions

There are several new possibilities to increase the color gamut of displays and at the moment the display industry is heavily investigating them. During the last years the existing direct view LCD solutions went through strong cost learning curves. Their next cost reduction target is to reduce the number of fluorescent tubes in the display module which, except for the solution with new lamp phosphors, makes it very doubtful whether any of the new color technologies will succeed to replace the existing direct view LCD display architecture in mass production soon. Furthermore, the MPC solutions are very promising for color-sequential systems like single panel DLP and new display systems.

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Ad de Vaan coordinates the technology management activities for the Multi-Media Displays business within Philips Consumer Electronics.
He received a B.Sc. degree in Physics from the University of Applied Sciences in Eindhoven and joined Philips research in 1980. He started with investigating LCD principles for television and data graphic applications. Since 1985 he has been focusing his work on Lightvalve projection and flat screen display technologies.
Ad de Vaan has over 100 issued or pending patents in the field of display technologies, like LCD drive schemes, brightness enhancement methods, projection principles, color display technologies and more.