A STUDY ON THE IMAGE QUALITY OF LIQUID CRYSTAL DISPLAY

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1. Introduction

Liquid Crystal Display (LCD) is a key technology in multimedia applications. Improving LCD image quality is one of the most important issues in the research and development of LCDs. Brightness and contrast are two major factors in determining the image quality of LCDs. Two main kinds of LCDs and their corresponding advanced modes have been developed and implemented. They are the Twisted Nematic Liquid Crystal Display (TN-LCD) mode and In-Plane-Switch Liquid Crystal Display (IPS-LCD) mode, respectively [1, 15]. In the TN-LCD mode, due to the operating principle of filtering light entering the TN-LCD mode by the polarizer, at least 50% of the light is eliminated and then the brightness of the display is weak. In addition, the contrast in the TN-LCD mode is decreased because the Liquid Crystal (LC) molecules are not completely perpendicular even with a full voltage applied [11]. Hence, contrast appears imperfect in the TN-LCD mode [6]. The IPS-LCD mode has made improvements in viewing angle characteristics [11]. However, in the IPS-LCD mode, more than 50% of light is also blocked by the polarizer, resulting in poor image brightness. Therefore, in order to improve the image quality of LCDs, developing an LCD mode with higher brightness and better contrast is one motivation of this thesis.

The Polymer-Dispersed technology can be employed to improve brightness of the LCD [2]. And Dual-Scan architecture [17] can be used to improve contrast of the LCD.

S. Agamanolis has pointed out that Polymer-Dispersed technology [2] could be one of future possibilities to improve brightness in [3]. However, the suggestion lacks evaluation and precise qualitative and quantitative analysis. T. Scheffer and J. Nehring have suggested that the Dual-Scan architecture could be a method to improve contrast, and this suggestion has been qualitatively illustrated in their work [17]. However, to date, the quantitative analysis and evaluation of the dual-scan architecture has yet not been finished. In addition, to our knowledge, no existing complete quantitative analysis of image brightness and contrast has yet been given for LCDs. Thus, providing a detailed analysis of image brightness and contrast from a quantitative point of view is another motivation of this thesis.

The objectives of this thesis are as follows:

- An analytical LCD mode, with Polymer-Dispersed technology [2] and dual-scan architecture [17], called the PDDS-LCD mode is proposed.
- The employment of Polymer-Dispersed technology [2] helps achieve a dramatically improved brightness but with limitation on improvement of image contrast.
- In order to address and resolve this problem, the Dual-Scan architecture [17] is employed.
- A detailed quantitative analysis and software simulation of image brightness and contrast is given.
- The quantitative analysis along with a software simulation shows and validates the technological benefits in term of structural simplicity as well as image quality.

In the next section, definitions and terminologies are introduced. In section 3, the operating principles of the TN-LCD and IPS-LCD modes are presented. In section 4, an analytical LCD mode, Polymer-Dispersed Dual-Scan Liquid Crystal Display (PDDS-LCD) and its structure and properties are developed. The operating principles of brightness and contrast in the PDDS-LCD mode are discussed in sections 5. In section 6, a detailed quantitative analysis of brightness and contrast of the PDDS-LCD mode compared to the TN-LCD and IPS-LCD modes is provided. The thesis closes with a brief conclusion.

2. Notations

In this section, we present some definitions and terminologies about this thesis.

Definition 1 (Luminosity) [27]

Luminosity is defined as the amount of light emitted or scattered by a surface. Luminance is the average of red, green, and blue color values that provide the perceived brightness of the combination. The English unit of measure for luminance is a foot-lambert (fL), and is defined as one foot-candle falling upon a perfectly diffusing white surface.

Definition 2 (Brightness[M1]) [27]

Brightness is defined as the luminosity of color, which can be expressed as luminous flux (lumen), luminous intensity (candela), luminance (candelas per square meter), and illuminance (lux).

Definition 3 (Pixel) [23]

A pixel is the smallest element of a display which can be assigned a color.

Definition 4 (Sub-pixel) [22]

A sub-pixel is a sub portion of a pixel showing only one of the primary colors - green, red or blue. Three or more sub-pixels make up a single pixel.

Definition 5 (Contrast[M2]) [28]

The contrast of an LCD is defined as the ratio of brightness of the pixel to that of the background. In all cases the numerator of the calculation should be the brighter value. It is a measure of the range of brightness content in an image. High contrast implies mainly dark-black and bright-white content; low contrast implies a small spread of gray values.

Definition 6 (Polarizer) [26, 28]

A polarizer is a device which creates polarized light when natural light enters upon it. It is made of a material that is used to convert a randomly un-polarized beam of light into a polarized one, oriented in such a way that light with $\mathbf{E}_2$ (electric vector) along the x axis is absorbed, while the $\mathbf{E}_1$ along the y axis is transmitted. It is shown in Figure 1.

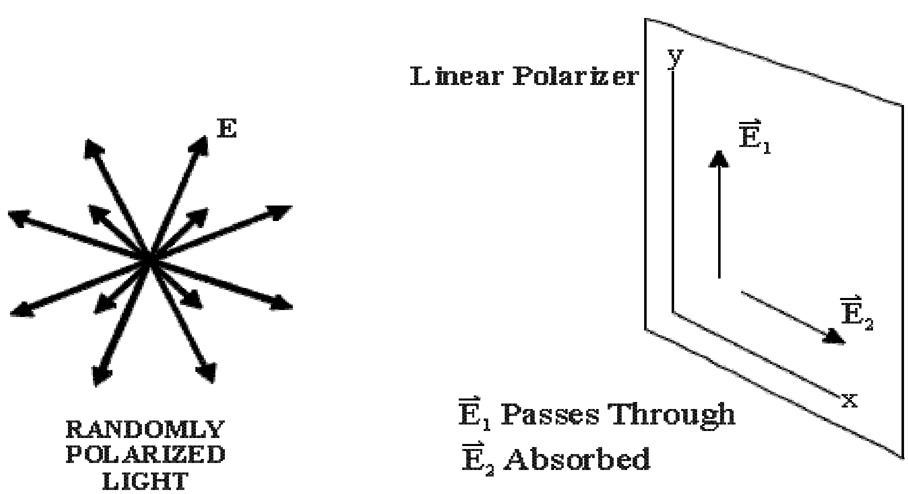


Figure 1[25]: Polarizer

Definition 7 (LC molecules) [28]

A Liquid Crystal (LC) molecule is a phase of matter whose order is intermediate between that of a liquid and that of a crystalline solid. The molecules are typically rod-shaped and about 25 angstroms in length. The ordering function of these LC molecules is a function of temperature.

Definition 8 (Nematic LCs) [29]

Nematic LCs are transparent or translucent liquids that cause the polarization of light waves to change as the waves pass through the liquid. The extent of the change in polarization depends on the intensity of an applied electric field. Nematic comes from the Greek prefix nemato meaning threadlike and is used here because the molecules in the liquid align themselves into a threadlike shape.

Definition 9 (ITO) [28, 35]

The acronym ITO stands for Indium Tin Oxide. ITO (In_2O_3) is a transparent conducting material that is usually used in thin coating form, and it is the patterned layer in a liquid crystal display.

Definition 10 (RGB) [21]

Short for Red-Green-Blue, RGB is a method of creating colors from the primary colors of red, green, and blue. RGB is used when describing a type of display or monitor.

Definition 11 (Twist angle) [35]

Twist angle is defined as the molecule orients roughly along the director, with a finite tilt angle, and a twist relative to other molecules.

Definition 12 (Beam geometry) [36]

Beam geometry is defined to specify the beam problem; it includes section properties, materials, boundary conditions etc.

3. General Principles of LCD Modes

The TN-LCD and IPS-LCD modes are two important types of existing LCDs, their operating principles are introduced as the following:

LC molecules have the following properties: they have the ordering properties of a solid, but flow like a liquid; they tend to be elongated and are oriented arbitrarily. Because of their elongated shape, LC molecules without the polymer exhibit order such that all LC molecules line up in a particular direction and form a nematic LC state. Under appropriate conditions, molecules are still able to move around in the fluid, but their orientation remains the same. Thus, when one speaks of “direction of the LC molecules”, this actually refers to the average direction of the molecules. This is shown in Figure 2.

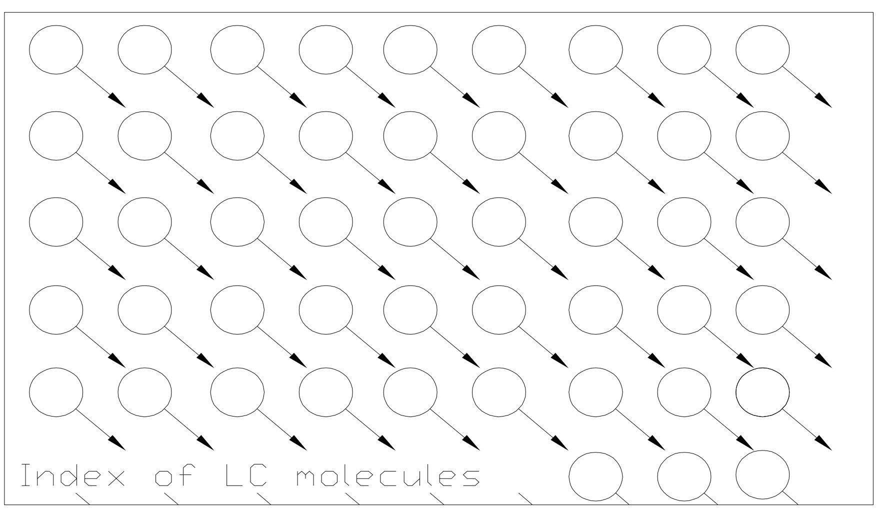


Figure 2: Properties of LC Molecules

The operating principles of the TN-LCD mode are shown in Figure 3. In the TN-LCD mode, each substrate generally consists of glass coated with a transparent conductive layer, such as ITO (Indium Tin Oxide). The innermost surfaces are prepared with a special alignment layer so that a 90^0 twist of the LC molecules is achieved. LC molecules are then sandwiched between two polarizers. The polarizing axes of the external polarizer can be parallel or perpendicular to the alignment layer rubbing direction. In the perpendicular mode, when no voltage is applied to the two transparent electrodes, light passes through the TN-LCD because the polarized light follows the twist. Polarized light goes through the second polarizer and produces white color on the display. When a voltage is applied, because of the electric anisotropic properties of the liquid crystal phase, the LC molecules will unwind and align parallel to the direction of the electrical field. In this situation, the polarization of the light remains unchanged [30]. Polarized light is blocked by the second polarizer and produces black color on the display.

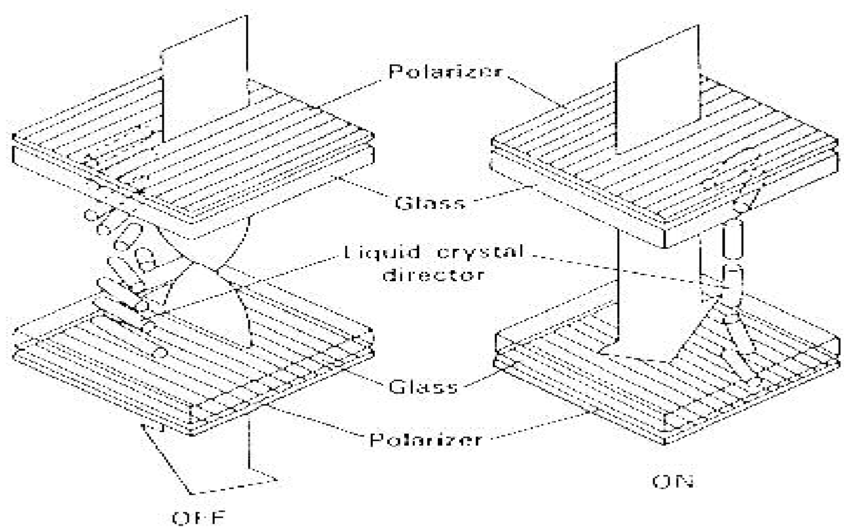


Figure 3 [30]: Operating Principle of TN-LCD Mode

Unfortunately, light entering the TN-LCD mode[M3] is filtered by the polarizer then eliminates at least 50%, which causes weak brightness on the display. Meanwhile, contrast in the TN-LCD mode is diminished because the LC molecules are not completely perpendicular even with a full voltage applying [11]. Hence, the white does not appear perfectly in the TN-LCD mode [6] as mentioned previously.

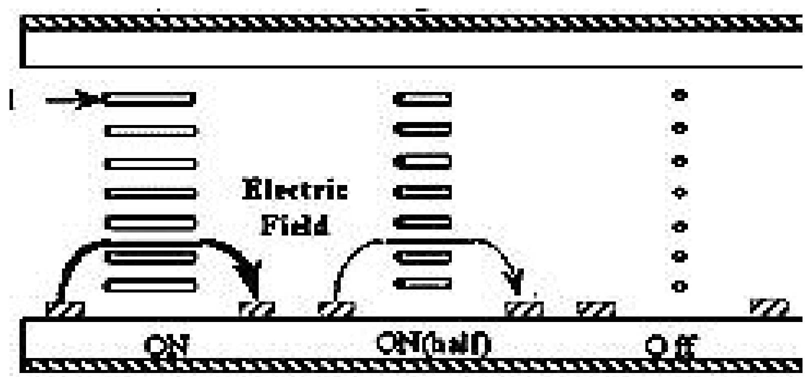


Figure 4 [31]: LC Molecules in IPS-LCD Mode

The operating principle of LC molecules in the IPS-LCD mode is shown as Figure 4, compared to the TN-LCD mode.

In the IPS-LCD mode, LC molecules are always lying parallel to the glass substrate if no voltage is applied. LC molecules rotate when a voltage is applied in that glass substrate and the rotation is determined by how much voltage applied while remaining parallel to the glass substrate, which achieves a wider viewing angle than the TN-LCD mode has. However, in the IPS-LCD mode, there is a similar unsatisfactory situation to the TN-LCD mode: 50% of the light is blocked by the polarizers, and results in a bad brightness.

As explained previously, twoexisting LCD modes, TN -LCD and IPS-LCD modes have the following common structures: their structures mainly consist of the polarizer[M4], which controls the light entering and leaving the display [15] and covers the glass substrate to prevent the filtering of electricity from electrodes [9]. The LC molecules [M5]are filled between two glass substrates, and small spacers among the LC fluid form a thin gap between the two glass substrates. Transparent electrodes are coated with glass substrates. Under the upper glass substrate is the color filter, which blocks all other wavelengths of light except those within the range it allows [8]. A layer of transparent electrodes coats the glass substrate, which drives the LC molecules[M6] [20]. Below those is a layer of microscopic grooves which align LC molecules in a fixed orientation; the microscopic groove, with the inner surface of glasses on plate, helps to align the orientation of LC molecules [14]. The microscopic groove layer can be a polymer of a soft tissue which has been unidirectionally rubbed; this result in the LC molecules being fixed in their alignment more or less parallel to the glass substrate, pointing along the rubbing direction which is an angle of nearly 90^0 between the upper and the lower glass substrates [29]. LC molecules reflect and refract the light entering the display. Spacers maintain a uniform gap between the glass substrates [5]. Then, another glass substrate and another polarizer follow up the layer of LC molecules. These finish the structures of the TN-LCD and IPS-LCD modes.

4. Polymer-Dispersed Dual-Scan Liquid Crystal Display (PDDS-LCD)

In this section, an analytical LCD mode, Polymer-Dispersed Dual-Scan Liquid Crystal Display (PDDS -LCD) mode is proposed. Its structure and properties are also illustrated.

4.1 The Structure of the PDDS-LCD Mode

The general structure of a PDDS- LCD mode assembly is shown in Figure 5.

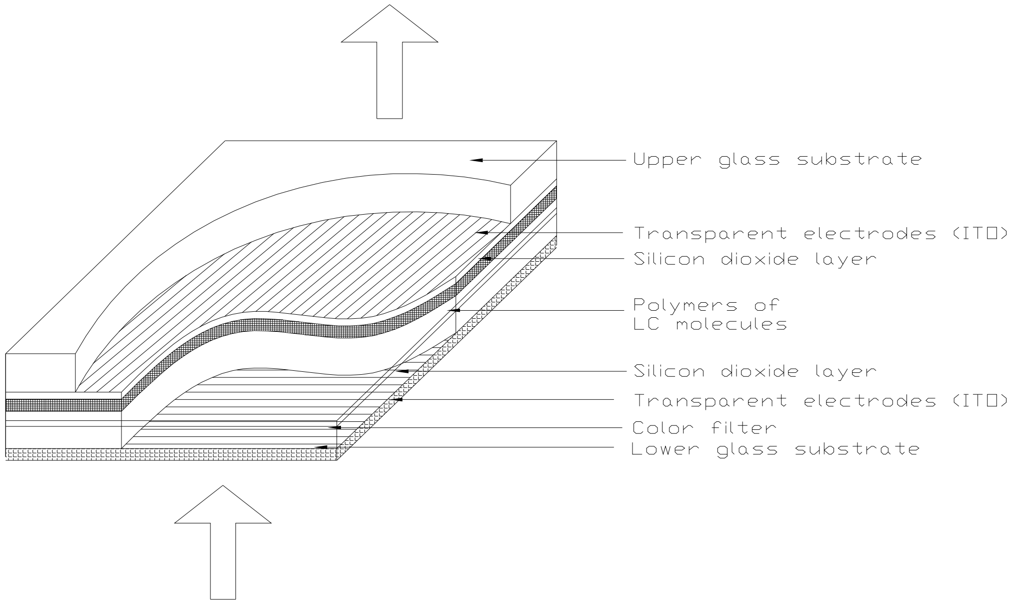


Figure 5 [30]: Structure of the PDDS-LCD Mode based on the Structure of the IPS-LCD Mode

As Figure 5 shows, the PDDS-LCD mode is simply a parallel plate capacitor with polymers of LC molecules between two glass substrates or transparent plastics. First, the glass substrate coated with a transparent metal serves as the electrodes of the display. The glass is usually a soda lime type [1], but can be a more expensive borosilicate type [19]. The transparent metal coating can be an ultra thin layer of any of numerous conductive materials, such as gold or silver. However, an Indium Tin Oxide (ITO)[M7] thin film is widely used to both to keep the cost down and to have a highly transparent coating. An insulating layer is placed on the top of the electrodes. The layer is normally composed of silicon dioxide and serves to seal the electrode surface and acting as an electrical barrier.

For the color PDDS-LCD mode, an additional color filter (usually made of glass) is integrated into the lower glass substrate, allowing the light to pass through it before entering the layer of polymers of LC molecules. A color filter is applied to the lower glass substrate of the LCD by using methods such as dye and pigment the application of pigment filter material that can be spun on the glass. The filter blocks all wavelengths of light except those within the range of that pixel. In a typical RGB display[M8], the color filter provides each individual sub-pixel with a primary color of red, green, or blue; each primary color has 256 degrees of intensity on a monochromic scale (that is from 0 to 255). The combination of these primary colors is used to produce the composite color of an image element (pixel). The areas in between the colored pixel filter areas are printed black to enhance contrast. After a beam of light passes through the color filter, three resulting sub-pixels of individual color with different gray scale overlap and form a single pixel with a resulting composite color. An image consists of millions of those pixels of different colors. Behind the color filter, a thin film of very small polymers of LC molecules (usually can be several hundred angstroms in diameter) is deposited onto the lower and upper glass substrates. The polymers of LC molecules have been carefully chosen for stability in an environment with high moisture and heat in order to avoid problems during storing and transportation. Another more essential feature of LC molecule polymers layer is the ability of LC molecules to align randomly, in many different directions, inside the polymer. LC molecules inside the transparent polymer thus take on many different orientations under proper conditions, which is called the Polymer-Dispersed characteristic. This is shown in Figure 6. The layer of polymers of LC molecules is covered by another glass substrate. In addition, special spaces with a diameter of several microns are used between the front and rear glass substrates in order to produce a slender fixed gap between the glass substrates.

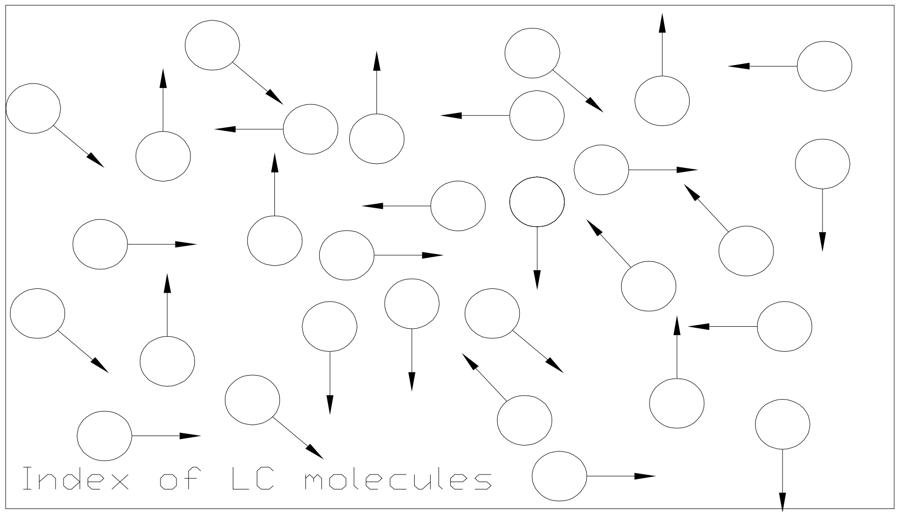
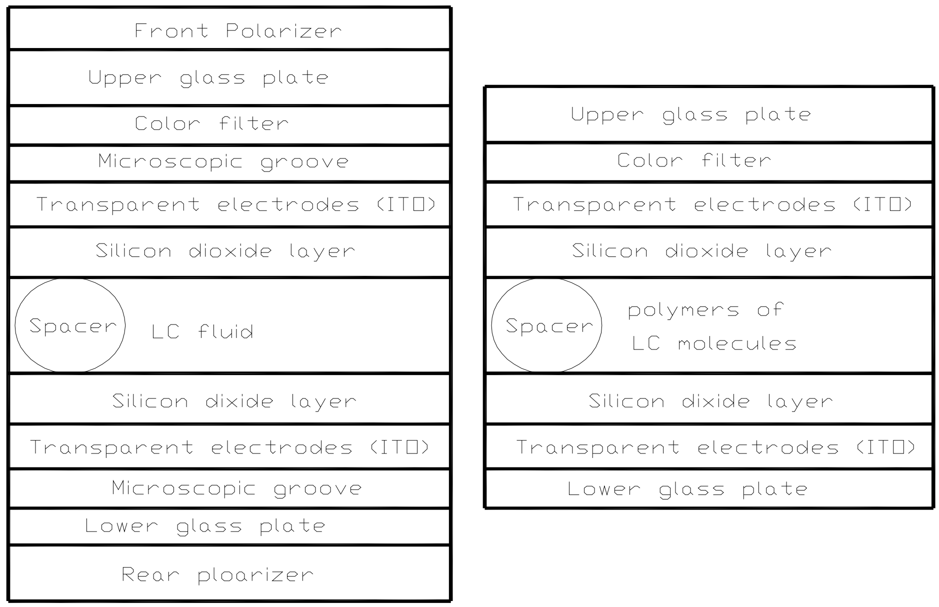


Figure 6: Polymer-Dispersed Characteristic of LC Molecules

A comparative view of the cross-sectional structures of the TN-LCD and IPS-LCD, and PDDS-LCD modes is shown in Figure 7. There are 12 layers in the TN-LCD and IPS-LCD modes (front polarizer, upper glass substrate, color filter, first microscopic groove, first transparent electrode (ITO), first silicon dioxide layer, spacers and LC fluid, second silicon dioxide layer, second transparent electrode (ITO), second microscopic groove, lower glass plate, and rear polarizer sequentially); In contrast, there are only 8 layers in the PDDS-LCD mode (upper glass substrate, color filter, first transparent electrodes (ITO), first silicon dioxide layer, spacers and polymers of LC molecules, second silicon dioxide layer, second transparent electrodes (ITO), and lower glass substrate, in order).



Left: TN-LCD and IPS-LCD Right: PDDS-LCD
Figure 7 [24]: Cross Sectional View of the Structures in Different Modes

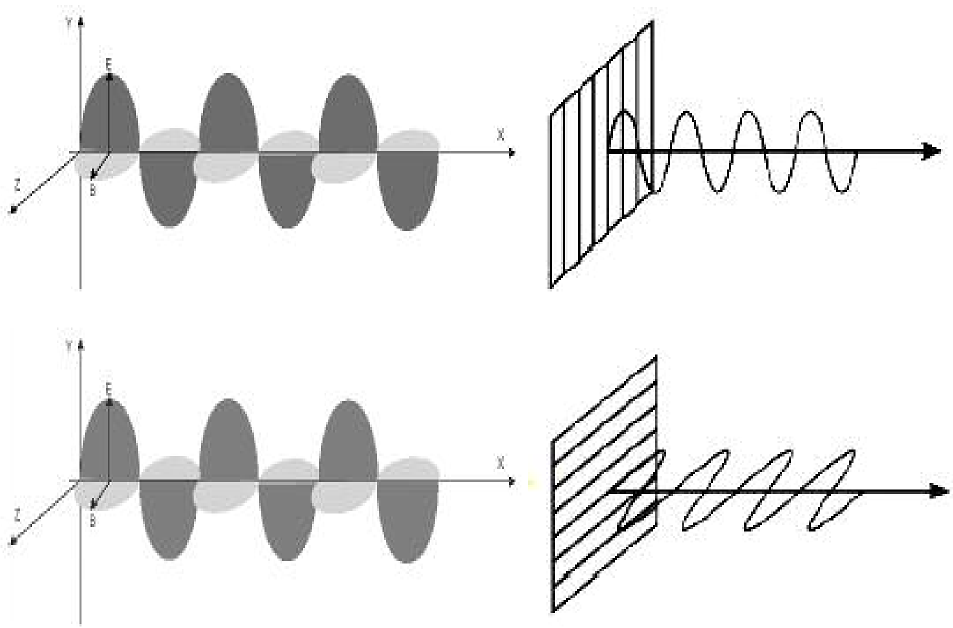
Obviously, as illustrated in Figure 7, the PDDS-LCD mode has the advantage of much structural simplicity compared to the TN-LCD and IPS-LCD modes. This simplicity results in a reduced manufacturing cost.

Also, in contrast to the TN-LCD and IPS-LCD modes, polymers of LC molecules are employed in the PDDS-LCD mode. The use of polymers of LC molecules makes the gap between the two glass substrates much larger. Thus, the PDDS-LCD mode is easier to manufacture since the gap between the two glass substrates is much larger than in the TN-LCD and IPS-LCD modes. The precision of the gap spacing in the PDDS-LCD mode is then not as important and has greater margins in an acceptable manufacturing specification.

4.2 Main Properties of the PDDS-LCD Mode

The PDDS-LCD mode has the following main properties in structure.

First, the PDDS-LCD mode is a polarizer-free structure. However, in other types of LCDs, such as the TN-LCD and IPS-LCD modes, particularly thin film serves as a polarizer to allow the transmission of light oscillating only in a certain plane. Light transmission through a polarizer in the TN-LCD and IPS-LCD modes is shown in Figure 8.

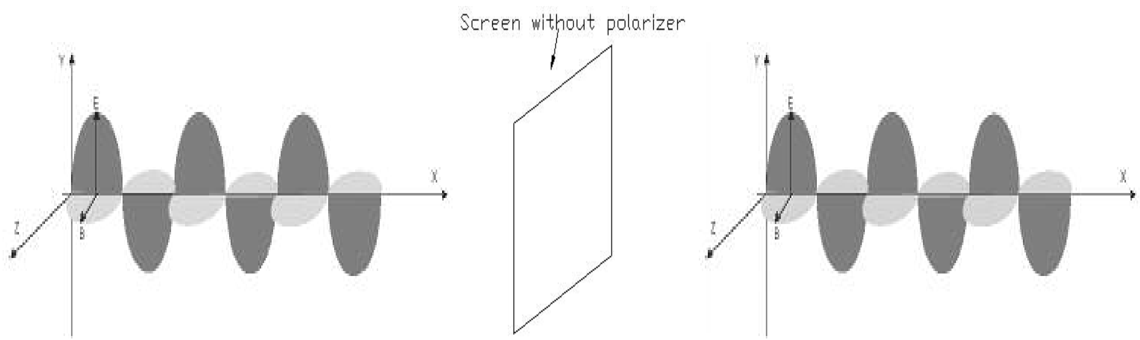


Left: Before Passes through Screen with Polarizer
Right: After Passes through Screen with Polarizer

Figure 8 [35]: Light Transmissions through Polarizer in the TN-LCD and IPS-LCD Modes

Light transmission through a polarizer in the TN-LCD and IPS-LCD modes is shown in Figure [M9]8. Incident light has both parallel and perpendicular relative directions as it enters the polarizer. The light cuts 50% and leaves the polarizer as polarized light. The component of the scattered light with polarization perpendicular to the polarizer orientation will be diminished while the component of the scattered light with polarization parallel to the polarizer orientation goes through the polarizer.

The transmission of light through an LCD panel without a polarizer as in the PDDS-LCD mode is shown in Figure [M10]9. Incident light with both parallel and perpendicular directions can pass through the lower glass, polymers of LC molecules and the upper glass while retain its both parallel and perpendicular directions because the PDDS-LCD mode has no polarizing filter.



Left: Before Passes through Screen without Polarizer
Right: After Passes through Screen without Polarizer

Figure 9: Light Transmission without Polarizer in the PDDS-LCD Mode

Second, the PDDS-LCD mode is a microscopically groove-free structure. However, in other LCD modes, such as the TN-LCD and IPS-LCD modes, microscopic groove [M11]is created on the inner surface of both glass substrates. This groove structure helps align the LC molecules more throughly. Even though LC molecules characteristically align along almost the same plane within an LC fluid [18], molecules near the surface tend to parallel the rubbing direction [18]. When LC molecules are put into the gap between the two glass substrates, if the LC molecule layer is thin enough, orientations of all the molecules inside the thin layer can be fixed. However, the Polymer-Dispersed characteristic of LC molecules results in the microscopic groove-free structure in the PDDS-LCD mode.

5. Operating Principles of the PDDS-LCD Mode

This section discusses the operating principles of brightness and contrast of the PDDS-LCD mode.

5.1 Brightness

In LCDs, brightness is measured as the luminance intensity of the components of light. There are two basic ways for lighting an LCD: the transmissively and the reflectively. Transmissive LCDs have clear polarizers on the front and back. The display depends on light coming through from the back of the display toward the observer in order to be seen [32]. The architecture of a transmissive LCD makes it usable in room environments with varying levels of ambient lighting. The operating principle of the transmissive LCD is shown in Figure 10.

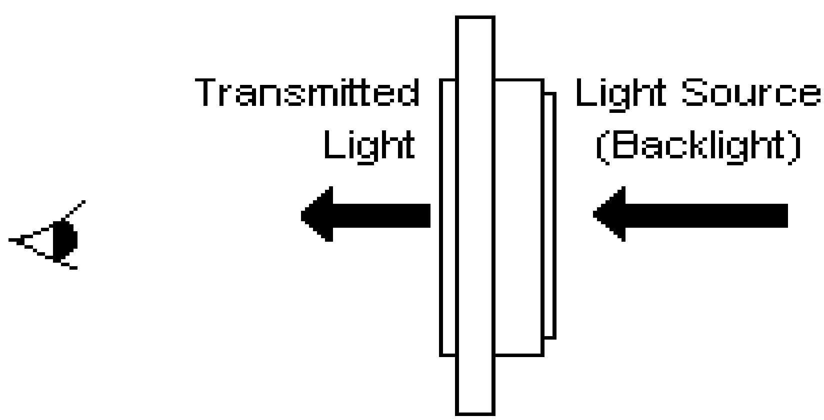


Figure 10 [32]: Transmissive LCD Lighting

Reflective displays have an opaque rear polarizer that includes a diffuse reflector, such as brushed aluminum. This layer reflects polarized ambient light that has entered the front of the display and has passed back through the LC molecules. Reflective displays require sufficient ambient light to be seen [32]. The reflective displays are particularly suitable for use in battery-operated equipment where an external light is always available. The architecture of a reflective LCD makes it suitable to be used in outdoor and other bright environments. The operating principle of the reflective is shown in Figure 11.

The PDDS-LCD mode presented in this thesis is designed for multimedia and computer applications. Since this use must accommodate indoor environments with low lighting, the PDDS-LCD mode is designed to work as a transmissive LCD.

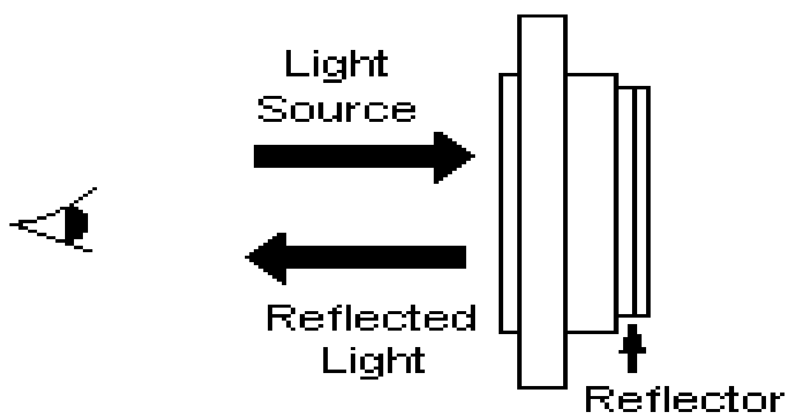
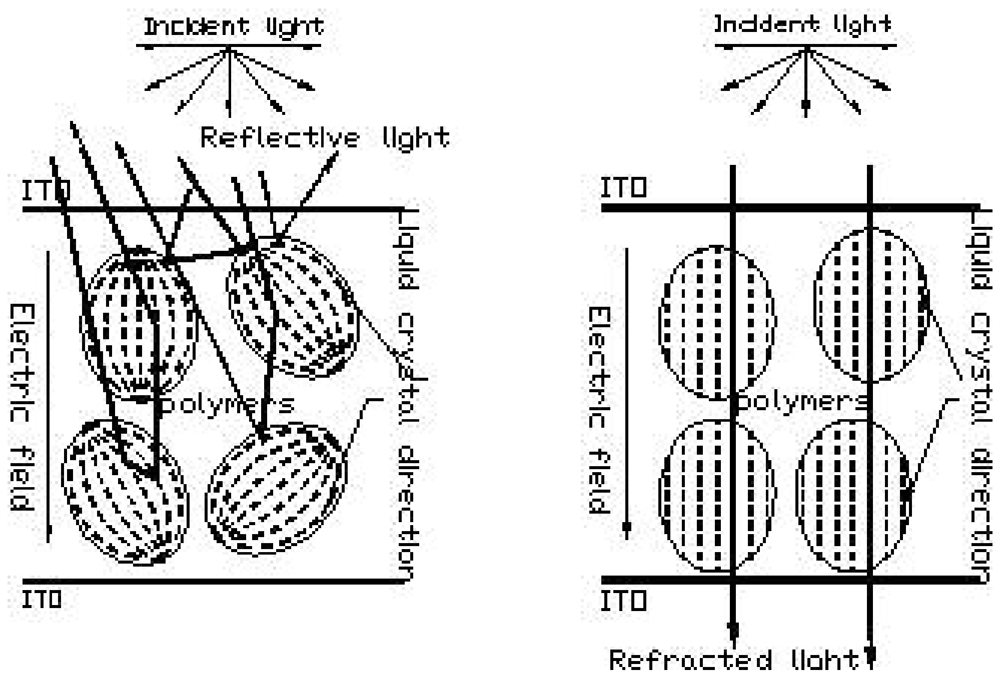


Figure 11 [32]: Reflective LCD Lighting

5.1.1 Scheme of Polymer-Dispersed LCD Technology [3]

In [3], S. Agamanolis suggested that polymer-dispersed LCD technology could be a possibility for improving the brightness in future displays. However, this suggestion did not provide evaluation and precise quantitative analysis. Polymer-Dispersed LCD technology can be used in the PDDS-LCD mode described in this thesis. A detailed evaluation and analysis of Polymer-Dispersed LCD technology for improving brightness in the PDDS-LCD mode will be given in the subsection of 6.1. The primary significant characteristic of the PDDS-LCD mode is that polymers of LC molecules are produced to replace the LC fluid used in the TN-LCD and IPS-LCD modes.



Left: "off" State; Black **Right: "on" State; White**

Figure 12: LC Molecules inside Polymers

If no voltage is applied, LC molecules inside polymers are in the "off" state, LC molecules inside polymers will take on many different orientations, as shown in Figure 6 previously. With the Polymer-Dispersed characteristic mentioned previously, there are mostly reflected from the incident light, leading to a black display on the LCD. When a voltage is applied, LC molecules inside polymer are in the "on" state, the direction of LC molecules will align with the field. If the material is carefully controlled, then the light will propagate all the way through the material without having any reflection in the polymers, which would lead to a white display. LC molecules in the “off” state and the “on” state are shown in Figure 12 [3].

5.1.2 Application of Polymer-Dispersed LCD Technology

The application of Polymer-Dispersed LCD technology in the PDDS-LCD mode achieves a high improvement in brightness for the PDDS-LCD mode due to the polarizer-free characteristic of the PDDS-LCD mode.

As illustrated in Figure 12, in pixels that are “off”, light is blocked by polymers of LC molecules when it passes through the color filter, the polymers, and the LC molecules. In pixels that are “on”, LC molecules inside the polymers re-orient their position with the LC directions nearly perpendicular to plane of the glass substrate, allowing the light to pass through the polymers of LC molecules.

When the PDSS-LCD mode is “addressed” by a voltage, most of the LC molecules inside the polymers twist from their alignments originally more or less parallel to plane of the glass substrate, pointing in a direction at an angle nearly 90^0 from the upper and the lower glass substrates. In actually, the twist angle of most of the LC molecules in the PDDS-LCD mode is somewhat less than 90^0 to the glass substrate while they are activated, resulting in an imperfection in image contrast. A detailed quantitative analysis of Polymer-Dispersed LCD technology for improving brightness in the PDDS-LCD mode will be given in subsection of 6.1.

5.2 Contrast

As stated above, the application of Polymer-Dispersed LCD technology causes an imperfect image contrast in the PDDS-LCD mode. In order to solve the drawback of imperfect image contrast, the Dual-Scan architecture [17] is employed to drive the PDDS-LCD mode.

5.2.1 Dual-Scan Architecture [17]

In [17], T. Scheffer and J. Nehring suggested the Dual-Scan architecture could be a method to improve contrast in LCDs. This suggestion has been qualitatively illustrated in their work. However, to date, this idea has not been quantitatively analyzed and evaluated. A detailed quantitative analysis of Dual-Scan architecture for improving contrast in the PDDS-LCD mode will be given in subsection 6.2.

Since the Dual-Scan architecture is based on traditional multiplexing driving technology, the principle of the multiplexing driving method is introduced in the following subsection.

5.2.1.1 Scheme of Multiplexing Driving Method [24]

Currently, the multiplexing driving method is a widespread method of driving LCDs, and it has been employed in the TN-LCD and IPS-LCD modes, due to the capacity of direct address. In the multiplexing driving method, pixels are arranged and wired in a matrix format. This is shown in Figure 13.

That is, all pixels across each row are connected together on one substrate, and all pixels in each column are connected on the opposite substrate. A positive voltage (+V) is applied to a row in sequence and then an opposite, negative voltage (-V) is applied to each column which needs to be switched. On the other hand, no voltage is applied to columns thatdo not need to be switched.

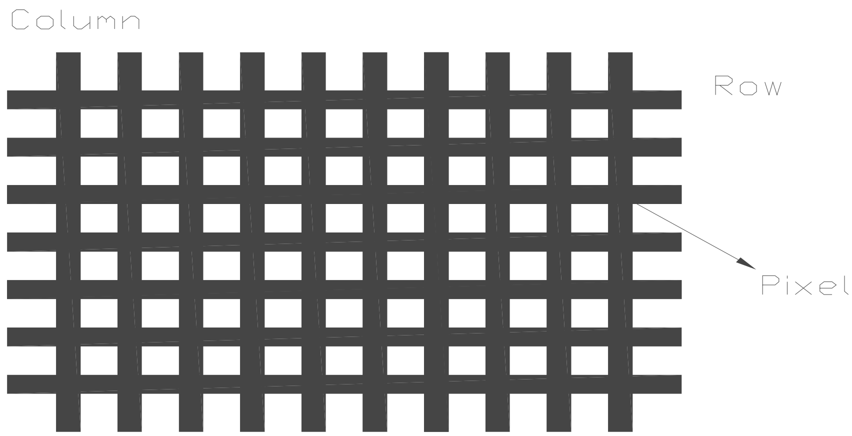
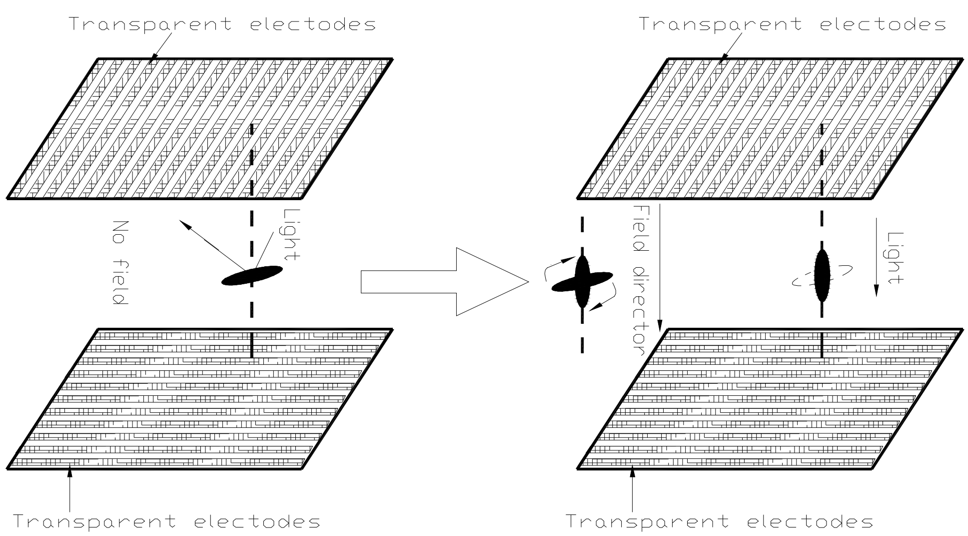


Figure 13: Pixels in Matrix Format

In the multiplexing driving method, direct address is used to drive the image element (pixel) in the display. The advantage of direct address is that it provides direct control over the pixel. In the multiplexing driving method, all pixels across each row are connected together on one side of the glass substrate, and all pixels in each column are connected together on the opposite side of the glass substrate. Those rows are then "addressed" serially (in order) by turning on the row voltages in sequence, while setting the respective column voltages simultaneously for each column containing a sub-pixel that needs to be activated on that row. When an activated row and activated column intersect, the LC molecule will be turned from the "off" state to the "on" state and hence forms a picture element (pixel) on the display.

In a color display, LC molecules are held between the two glass substrates, as shown in Figure 14. These substrates are manufactured with transparent electrodes, typically made of ITO, which allows light to enter the glass substrate. Transparent elements and color filters form sub-pixels inside the substrates. This structure makes it possible to apply an electrical field across a small area of LC molecules. The color of the pixel is defined by a composite of individual colors using red, green, or blue sub-pixels with different values on a monochromatic scale. While driving a picture element (sub-pixel) in the LCD, two properties of LC molecules decide which picture elements (sub-pixels) are able to turn "on" and "off" by electrical field switching: first, upon applying an electrical field, the alignment of the LC molecules is charged with the field's polarization property; second, when light passes through the transparent LC molecules, the orientation of the polarized light can be altered by the switching of LC molecules.



Left: "off" State Right: "on" State

Figure 14: LC Molecule Is Activated

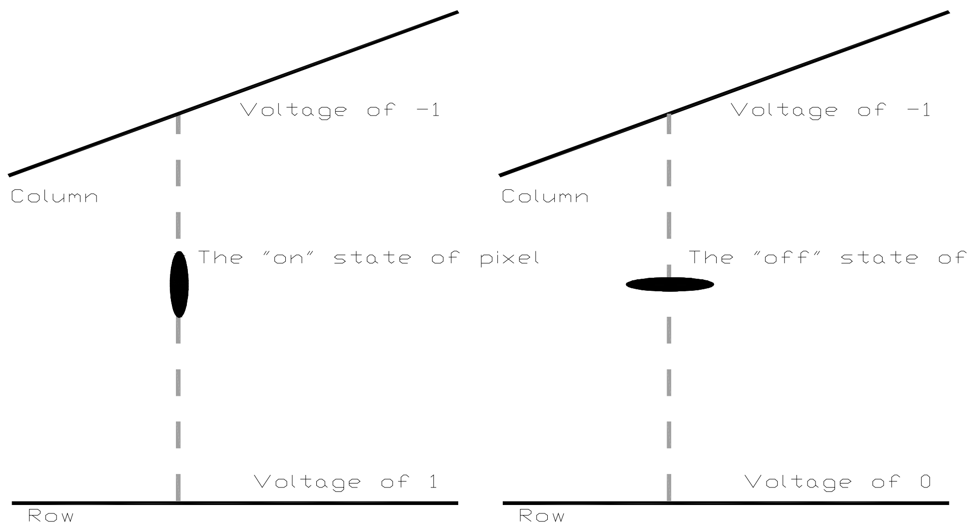
For an image to appear on the screen, one row of pixels receives an appropriate voltage. At the same time, software in the computer dictates that voltage be applied to those columns holding active sub-pixels. Where the activated row and an activated column intersect, they turn on the electrode generating an electrical field that controls the orientation of the LC molecule. The process of a LC molecule being turned from the "off" state to the "on" state by an activated row and activated column of electrodes is shown in Figure 14.

If an LCD has N rows on the one side of the glass substrate and M columns on the substrate on the opposite side, the number of pixels required to produce a picture can be calculated by using Formula 1:

$$P = N \times M \qquad \mathbf{(1)}$$

where P represents the number of sub-pixels of a picture area, N represents the number of rows on the substrate of one side of the glass substrate, and M represents the number of columns on the opposite side of the glass substrate. The multiplexing driving method is able to control $N \times M$ number of image elements by handling just $N + M$ number of electrodes.

However, the multiplexing driving method also has a disadvantage in its contrast quality. All N rows must share each voltage pulse as a time slice. Thus, if there are N rows in the large display, then as the activation cycles through each row, the pixels in a given row will be receiving the availablevoltage for only 1/N of the pulse time. This means that the activated pixels in a given row will be at maximum contrast for only 1/N of the pulse time. As mentioned previously, a voltage of $+V$ is applied to each row in sequence, and a voltage of $-V$ is applied simultaneously only to each column which needs to be switched. As a result, during the rest of the time ((N-1)/N) when later rows are being addressed, the pixels in previous rows will experience a smaller net voltage (0-(-V)) than the activated rows do (V-(-V)) [13]. Therefore, the pixels never really maintain a full “on” or “off” voltage; they are almost always somewhere in between. Since the image contrast of the LCD depends on how close the voltages of the rows are [2], the use of the multiplexing driving method in LCDs results in imperfect contrast in the TN-LCD and IPS-LCD modes. Thus, it is inappropriate to employ multiplexing driving in the PDDS-LCD mode if a better contrast than TN-LCD and IPS-LCD modes have is available.



Left: “on” State Right: “off” State
Figure 15: Voltages Addressed on Electrodes

A row would have a positive voltage of 1 if it is addressed and a voltage of 0 if it is not. In the mean time, voltage is addressed to the column which corresponds to the pixel needs to be in the “on” state. If a certain pixel is in the “on” state, it holds a column of a voltage of -1, otherwise, it is 0. Voltage addressed on the row and its corresponding column in the “on” state (the left) v.s. “off” state (the right) state of the pixel is shown as Figure 15.

5.2.1.2 Scheme of Dual-Scan Architecture [27]

Compared to the multiplexing driving method, the Dual-Scan architecture applied in the PDDS-LCD mode provides an improvement in image contrast. In [27], it was mentioned that the core principles of the Dual-Scan architecture was developed from some previously LCD technology. In the late 1970's and early 1980's liquid crystal chemistry was not as advanced and in order to build high data content displays, two displays on one glass substrate were built by manufacturers. The Dual-Scan technique utilizes a similar principle. In the PDDS-LCD mode, instead of running the columns down the entire display, columns are terminated in the center of the display. A small gap is then left, and a new column is continued to the bottom of the display. Therefore, if voltage is "addressed" on the top and the bottom of the display, the charge must travel only half the distance of a normal display [27]. The Dual-Scan architecture is shown as Figure 16.

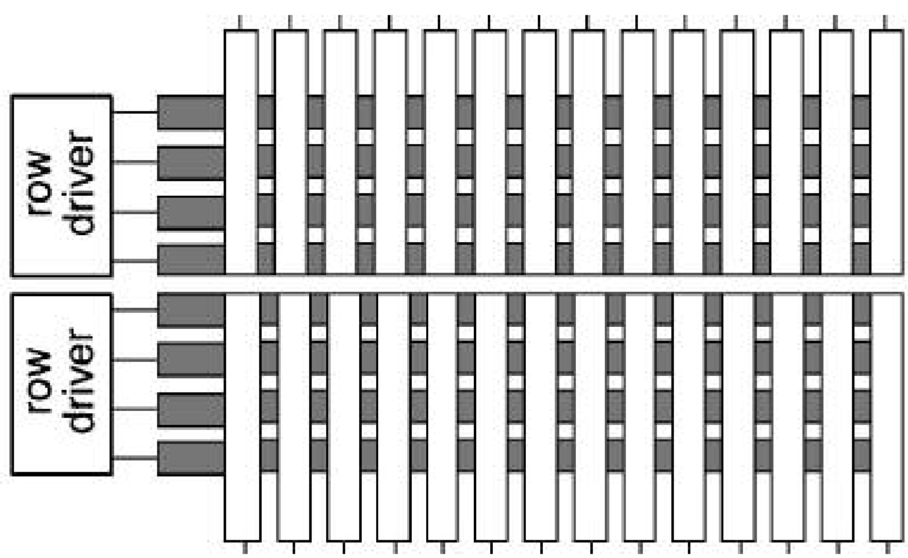


Figure 16 [27]: Dual-Scan Architecture

In Figure 16, the glass substrate on which the rows are placed in the LCD is divided into two sections. The rows in each section are scanned by an individual voltage.

Hence, employing the Dual-Scan architecture halves the number of rows in each separate display .

5.2.2 Application of Dual-Scan Architecture

To improve image contrast, the Dual-Scan architecture is used to drive the image elements (sub-pixels) in the PDDS-LCD[M12] mode. A detailed quantitative analysis of the Dual-Scan architecture for improving contrast in the PDDS-LCD mode will be given in subsection 6.2.

6. Image Quality Analysis of the PDDS-LCD Mode

6.1 Quantitative Analysis of Brightness

In LCDs, brightness is measured as the luminance intensity of the components of light parallel and perpendicular to the polarizer. Incident light has both parallel and perpendicular directions with respect to the polarizer as shown in Figure 7 previously. Let I be the components of the incident light, $I_{//}$ be the component of the scattered light with polarization in the parallel direction with the polarizer, and $I_{\perp}$ be the component of the scattered light with polarization in the perpendicular direction with the polarizer.

Since the angle between the directions of $I_{//}$ and $I_{\perp}$ is always equal to 90^0, we have the following equation

$$I = \sqrt{I_{//}^{\ 2} + I_{\perp}^{\ 2}} \qquad \textbf{(2)}$$

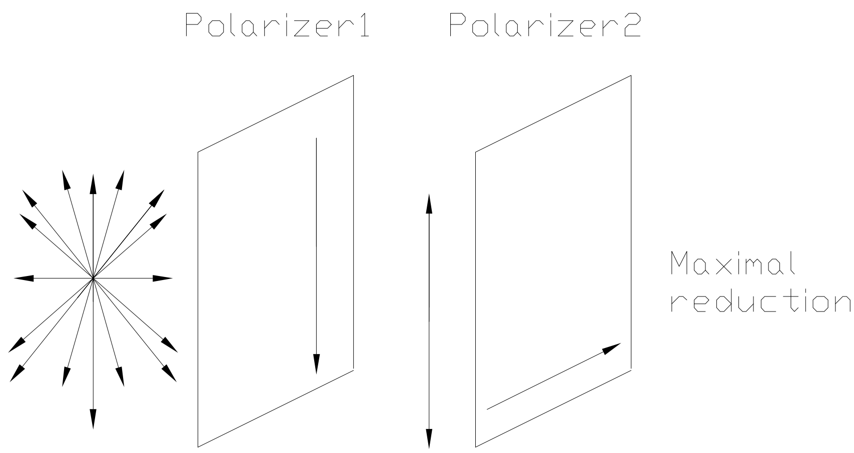


Figure 17: Light Transmission through Two Consequent Polarizers

In LCD modes, the luminance intensity of the scattered light of $I_{//}$ and $I_{\perp}$ is defined as $I_{//}^{\ *}$, and $I_{\perp}^{\ *}$, respectively. If the incident light passes through polarizers, one after the other, then the intensity of the transmitted light depends on the difference between the polarizer directions. If the polarizer axes are parallel, the second polarizer has no effect on the polarized light and makes no change in the resulting intensity. In other cases, the second polarizer further reduces the intensity. Let α be the angle between the direction of the polarized light and the orientation of the second polarizer, and then reduction of light is maximal in the case that α is equal to 90°. This is shown as Figure 17.

According to the law of Malus in [16], the intensity of light is directly proportional to the square of the amplitude of the scattered light. Since the amplitudes of the components of the scattered light with polarizations in the parallel direction and in the perpendicular direction are $I_{//}\cos\alpha$ and $I_{\perp}\cos\alpha$, respectively. Thus, the intensity of the scattered light with polarizations in the parallel direction and in the perpendicular direction can be derived from the two following formulas, respectively.

$$I_{//}^{*} = I_{//}^{2} \cos^{2} \alpha \qquad \textbf{(3)}$$

and

$$I_{\perp}^{*} = I_{\perp}^{2} \cos^{2} \alpha \qquad \textbf{(4)}$$

In addition to polarizing effects, LCD luminosity is also determined in partly the reflection or refraction of light incident upon a screen. In a back-lit LCD, light entering the lower glass from the back of the LCD is divided into both reflected and refracted components. An illustration of the reflected and refracted components derived from incident light when it enters the glass is shown in Figure 18.

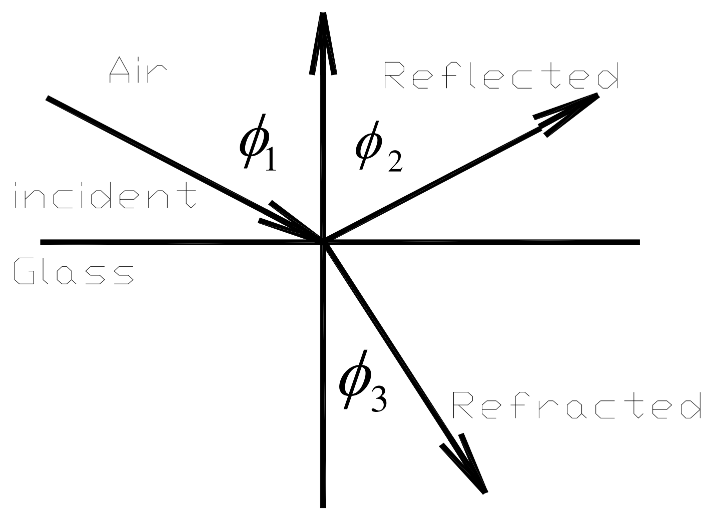


Figure 18: Incident Light Divided into Reflected and Refracted Components

As illustrated in Figure 18, at the boundary of two different media (e.g., air and glass), a part of the incident light is reflected back from the boundary and another portion of the incident light is refracted. Let n_1 be the index of refraction of air and n_2 be the index of refraction of glass, according to the Fresnel equations [26], the angle of reflection is always equal to the angle of incidence. The refracted angle depends on the indices of refraction of the media. We have

$$\phi_1 = \phi_2 \qquad \textbf{(5) [26]}$$

and

$$n_1 \sin\phi_1 = n_2 \sin\phi_3 \qquad \textbf{(6) [26]}$$

Follows, a detailed derivation on getting the reflection and refraction coefficients is given.

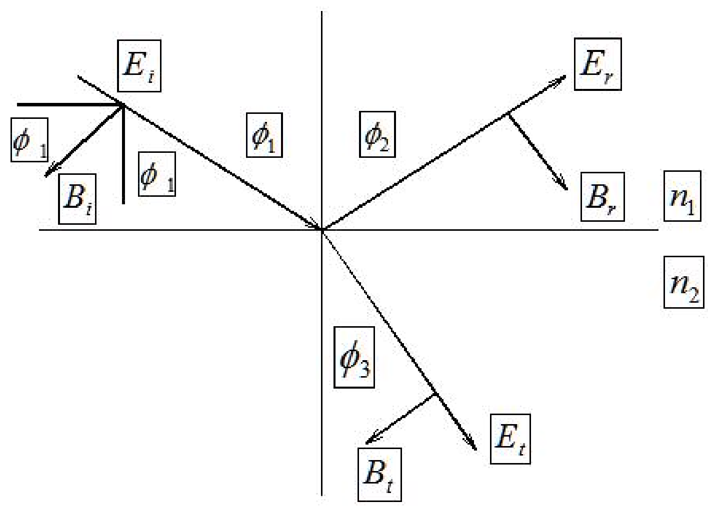


Figure 19 [33]: Light Amplitude and Beam Geometry through Interface

In Figure 19, E_i represents the amplitude of the incident light, E_r represents the amplitude of the reflected component, and E_t represents the amplitude of the refracted component. B_i represents the beam geometry for the incident light, B_r represents the beam geometry for the reflected light, and B_t represents the beam geometry for the refracted light. Note that E_i, E_r, E_t, B_i, B_r and B_t are all vectors, thus, for perpendicular light we have

$$E_i + E_r = E_t \qquad \textbf{(7) [33]}$$

$$-B_i \cos\phi_1 + B_r \cos\phi_2 = -B_t \cos\phi_3 \qquad \textbf{(8) [33]}$$

and

$$B = E/(C_0/n) = nE/C_0 \qquad \textbf{(9) [33]}$$

where, n represents the index of refraction of the media employed, C_0 represents the speed of light in air, and E has the same definition as shown in Figure 17.

By using equations 5, 7, 8 and 9, we have

$$n_1(E_r - E_i)\cos\phi_1 = -n_2 E_t \cos\phi_3 \qquad \textbf{(10) [33]}$$

Then substituting for E_t using equation 7, we have

$$n_1(E_r - E_i)\cos\phi_1 = -n_2(E_r + E_i)\cos\phi_3 \qquad \textbf{(11) [33]}$$

By rearranging equation 11, we have

$$E_r(n_1 \cos\phi_1 + n_2 \cos\phi_3) = E_i(n_1 \cos\phi_1 - n_2 \cos\phi_3) \qquad \textbf{(12) [33]}$$

Since the reflection coefficient is defined as the luminance intensity for the reflected light divided by the luminance intensity for the incident light, and the intensity coefficients are often defined as the square of the corresponding amplitude coefficients [7], that is $\left(\frac{E_r}{E_i}\right)^2$. Let $R_\perp$ be the intensity reflection coefficient of the component of the scattered light with polarization in the perpendicular direction, $R_\perp = \left(\frac{E_r}{E_i}\right)^2$ can then be solved by using equation 13 as

$$R_{\perp} = \left(\frac{E_r}{E_i}\right)^2 = \left(\frac{n_1 \cos\phi_1 - n_2 \cos\phi_3}{n_1 \cos\phi_1 + n_2 \cos\phi_3}\right)^2 \qquad \textbf{(13) [34]}$$

Analogously, the refraction coefficient is defined as the luminance intensity for the refracted light divided by the luminance intensity for the incident light, and the intensity coefficients are defined as the square of the corresponding amplitude coefficients [7] as mentioned previously, that is $\left(\frac{E_t}{E_i}\right)^2$. Let $T_{\perp}$ be the intensity refraction coefficient of the component of the scattered light with polarization in the perpendicular direction. Then $T_{\perp} = \left(\frac{E_t}{E_i}\right)^2$ can be solved as

$$T_{\perp} = \left(\frac{E_t}{E_i}\right)^2 = \left(\frac{2n_2 \cos\phi_3}{n_1 \cos\phi_1 + n_2 \cos\phi_3}\right)^2 \qquad \textbf{(14) [34]}$$

For parallel light, as shown in Figure 19, we have

$$B_i - B_r = B_t \qquad \textbf{(15) [33]}$$

and

$$E_i \cos\phi_1 + E_r \cos\phi_2 = E_t \cos\phi_3 \qquad \textbf{(16) [33]}$$

By using equations 5, 9, 15 and substituting for E_t equation 16 yields

$$n_1(E_i - E_r)\cos\phi_3 = n_2(E_i + E_r)\cos\phi_1 \qquad \textbf{(17)}$$

Rearranging equation 17 yields

$$E_i(n_1 \cos\phi_3 - n_2 \cos\phi_1) = E_r(n_1 \cos\phi_3 + n_2 \cos\phi_1) \qquad \textbf{(18)}$$

As discussed previously with respect to $R_{\perp}$, the reflection coefficient is defined as the intensity for the reflected light divided by the intensity for the incident light, and the intensity coefficients are often defined as the square of the corresponding amplitude coefficients [7] as mentioned previously, that is $\left(\frac{E_r}{E_i}\right)^2$. Let $R_{//}$ be the intensity reflection coefficient of the component of the scattered light with polarization in the parallel direction, and then $R_{//}=\left(\frac{E_r}{E_i}\right)^2$ can be solved by using equation 18 as

$$R_{//}=\left(\frac{E_r}{E_i}\right)^2=\left(\frac{n_1\cos\phi_3-n_2\cos\phi_1}{n_1\cos\phi_3+n_2\cos\phi_1}\right)^2 \qquad \textbf{(19) [34]}$$

Analogously, the refraction coefficient is defined as the light intensity for the refracted light divided by the light intensity for the incident light, and the intensity coefficients are often defined as the square of the corresponding amplitude coefficients [7] as mentioned previously, that is $\left(\frac{E_t}{E_i}\right)^2$. Let $T_{//}$ be the intensity refraction coefficient of the component of the scattered light with polarization in the parallel direction. Then $T_{//}=\left(\frac{E_t}{E_i}\right)^2$ can be solved as

$$T_{//}=\left(\frac{E_t}{E_i}\right)^2=\left(\frac{2n_1\cos\phi_1}{n_1\cos\phi_3+n_2\cos\phi_1}\right)^2 \qquad \textbf{(20) [34]}$$

Note that in the PDDS-LCD mode, there is no difference between the component of the scattered light with polarization in the parallel direction and the component of the scattered light with polarization in the perpendicular direction. Thus, by combining the equations 13, 14, 19 and 20 in the case of $\phi_1 = \phi_2 = \phi_3 = 0$, we have

$$R_{//,\perp} = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2 \qquad \textbf{(21) [26]}$$

and

$$T_{//,\perp} = \frac{4n_1 n_2}{(n_2 + n_1)^2} \qquad \textbf{(22) [26]}$$

Light transmission in the LCD is illustrated in Figure 20.

In a back-lit LCD, incident light precedes its division on interface of air and the lower glass substrate and divides into the refracted component and the reflected component of the incident light. The refracted component of the incident light passing through the lower (first-level) glass, goes through the second stage of light division at the interface of the lower glass and the layer of LC molecules. The refracted component of the light at this second stage passes through the layer of LC molecules, and experiences a third level of light division at the interface of the layer of the LC molecules and the upper glass. Subsequently, the refracted component of the light at the third stage passes through the upper glass, and goes through the fourth stage of light division at the interface of the upper glass and the air. Finally, the refracted component of the light at the fourth stage exits the upper glass. The component of light leaving the upper glass into the air and entering human eyes is the only component of light which produces the brightness of the LCD.

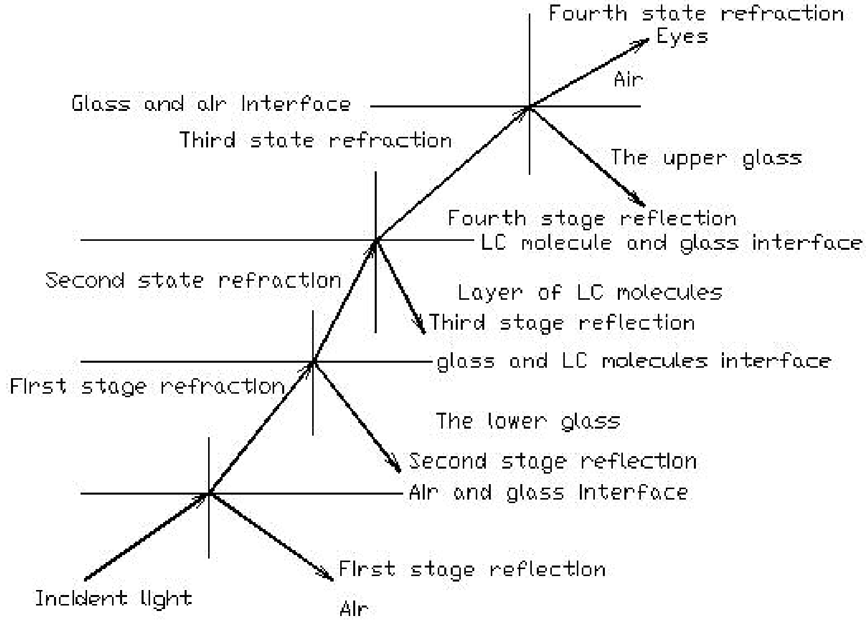


Figure 20: Light Transmission in the LCD

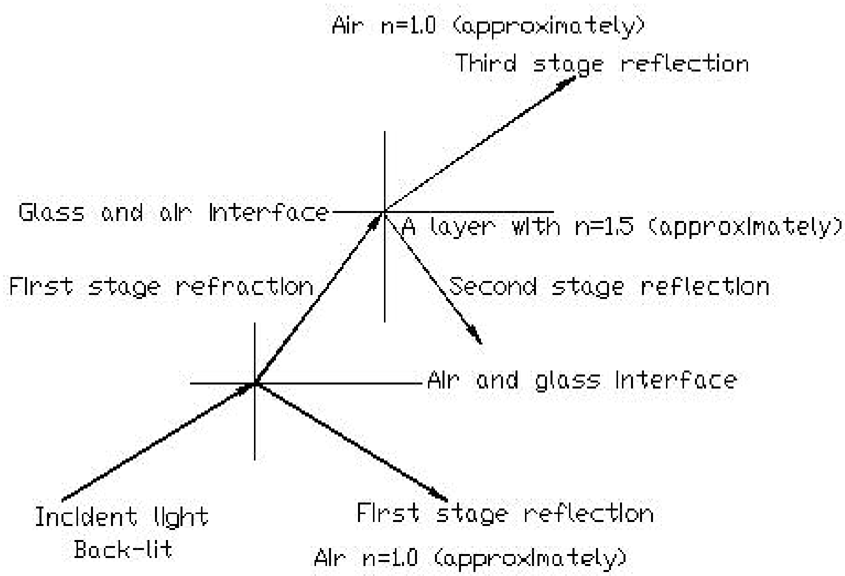


Figure 21: Simplification of Light Transmission in the LCD

On the other hand, in [33], the index of refraction of the LC molecules is from 1.4792 to 1.5632 [33], which approximately equals to the index of refraction of glass ($n_2 \approx 1.5$), Thus, for simplifying calculation, it is permissible to consider layers of the lower glass, LC material and upper glass as a single layer which approximately has the index of refraction of 1.5. Therefore, light transmission in LCD can be simplified to Figure 21.

In addition, the index of refraction of air n_1 is approximately equal to 1, and the index of refraction of glass n_2 is approximately equal to 1.5 [33]. That is, $n_1 \approx 1$, and $n_2 \approx 1.5$. Hence, by substituting the indices of air and glass into equations 21 and 22, in case of light from glass passing through air only, we have

$$R_{//,\perp} = \left(\frac{1.5-1}{1.5+1}\right)^2 = \left(\frac{0.5}{2.5}\right)^2 = 0.04 = 4\%$$

and

$$T_{//,\perp} = \frac{4\times1\times1.5}{(1.5+1)^2} = \frac{6}{(2.5)^2} = \frac{6}{6.25} = 0.96 = 96\%$$

As illustrated in Figure 21, the reflected component ($\approx 4\%$) of the incident light (which is separated at the interface of air ($n \approx 1$) and the layer whose index of refraction of approximately equal to 1.5 ($n \approx 1.5$) is very small. The refracted component ($\approx 96\%$ of the incident light) passes through the layer whose index of refraction approximately equals to 1.5 ($n \approx 1.5$) and undergoes another division at the interface of that layer and air before it reaches human eyes.

In addition, when computing the brightness of LCDs, it is permissible to ignore the reflected components of light blocked by the various interfaces, because the reflected components comprise only 4% of their corresponding incident light components. Thus, only the intensity refraction coefficient $T_{//,\perp}$ needs to be considered in calculating the brightness of LCDs.

In the PDDS-LCD mode and other LCD modes with polarizers such as TN-LCD and IPS-LCD modes, the incident light comes from air to a layer whose index of refraction approximately equals to 1.5 (that is, $n \approx 1.5$), then leaves that layer into the air. Hence, the value of the indices of refraction of n_1 and n_2 chosen in all modes (PDDS-LCD, TN-LCD, and IPS-LCD) are the same.

However, all LCD modes do not have the same transmissive properties, in particularly in regard to the filtration of light due to polarizers. In the TN-LCD and IPS-LCD modes, when incident light I passes through a polarizer of perpendicular direction, the component $I_{//}$ of the scattered light with polarization parallel to the incident light will be blocked, and only the components $I_{\perp}$ with polarization perpendicular to the incident light will pass through the polarizer. Similarly, when incident light I passes through the polarizer of parallel direction, the component $I_{\perp}$ of the scattered light with polarization perpendicular to the incident light will be blocked, and only the component $I_{//}$ with polarization parallel to the incident light will pass through the polarizer. As a result, in TN-LCD and IPS-LCD modes, either the components $I_{//}$ of the scattered light with polarizations parallel to the incident light or the component $I_{\perp}$ of the scattered light with polarization perpendicular to the incident light is blocked. As mentioned before, incident light is filtered 50% as it passes through the polarizer in the TN-LCD and IPS-LCD modes and comes out as polarized light. Hence only 50% of light is left after polarization to pass through the color filter and the LC molecules.

Let B_{TI} denote the brightness of the TN-LCD and IPS-LCD modes, then the brightness formula of the TN-LCD and IPS-LCD modes is

$$B_{TI} = \left(I_{//}{}^{*}\right)T_{//}{}^{2}\cos^2 a = \left(I_{\perp}{}^{*}\right)T_{\perp}{}^{2}\cos^2 a = (I_{//}{}^{2})\left(\frac{4n_2n_1}{(n_2+n_1)^2}\right)^2\cos^2\alpha \qquad \textbf{(23) [37]}$$

$$= (I_{\perp}{}^{2})\left(\frac{4n_2n_1}{(n_2+n_1)^2}\right)^2\cos^2\alpha$$

where, $I_{//}$, $I_{\perp}$, α, n_1 and n_2 have the same definitions as in Formulas 3-22.

On the other hand, in the PDDS-LCD mode, due to its polarizer-free characteristic, both the component $I_{//}$ and $I_{\perp}$ of the scattered light (those with polarization parallel to the incident light those with polarization perpendicular to the incident light) pass through the color filter, the polymers and the LC molecules. The component intensities are additive with respect to net intensity must be noticed. Thus, in the PDDS-LCD mode, as in the other modes, the intensities of the reflected and refracted components depend on the intensity reflection and intensity refraction coefficients [10]. By Formulas 3, 4 and 22, the intensities of light (brightness) coming from the PDDS-LCD mode (as well as from other modes) and producing the brightness are

$$(I_{//}{}^{*} + I_{\perp}{}^{*})T_{//,\perp}^{*}{}^{2} \qquad \textbf{(24) [37]}$$

where, $T_{//,\perp}$ is the intensity refraction coefficient. The square of $T_{//,\perp}$ is needed because the first $T_{//,\perp}$ factor is involved as light meets the boundary from air to the layer whose index of refraction of approximately equal to 1.5 (n$\approx$1.5); the second $T_{//,\perp}$ factor is involved as light meets the boundary from the layer whose index of refraction of approximately equal to 1.5 ($n \approx 1.5$) to air. The application of these coefficients is multiplicative.

Let B_p denotes the brightness of the PDDS-LCD mode; replace Formulas 3, 4 and 22 into Formula 24, then the brightness formula of the PDDS-LCD mode is

$$B_p = \left(I_{//}^* + I_{\perp}^*\right)T_{//,\perp}^2 \cos^2 a = (I_{//}^2 + I_{\perp}^2)\left(\frac{4n_2 n_1}{(n_2 + n_1)^2}\right)^2 \cos^2 \alpha \qquad \textbf{(25) [37]}$$

where, $I_{//}$, $I_{\perp}$, $T_{//,\perp}$ α , n_1 and n_2 have the same definitions as in Formulas 3-24.

Assume that the component of the scattered light with polarization in the parallel direction and the component of the scattered light with polarization in perpendicular direction have the same probability. That is, on average the incident has 50% polarization in the parallel direction, and 50% polarization in the perpendicular direction. In the PDDS-LCD mode, both of the components pass through the color filter, the polymers, and the LC molecules in the PDDS-LCD mode.

The ratio of the brightness of the PDDS-LCD mode to the brightness of the TN-LCD and IPS-LCD modes can therefore be calculated as

$$\frac{B_P}{B_{TI}} = \frac{(I_{//}^2 + I_{\perp}^2)\left(\frac{4n_2 n_1}{(n_2 + n_1)^2}\right)^2 \cos^2 \alpha}{(I_{//}^2)\left(\frac{4n_2 n_1}{(n_2 + n_1)^2}\right)^2 \cos^2 \alpha} = \frac{(I_{//}^2 + I_{\perp}^2)\left(\frac{4n_2 n_1}{(n_2 + n_1)^2}\right)^2 \cos^2 \alpha}{(I_{\perp}^2)\left(\frac{4n_2 n_1}{(n_2 + n_1)^2}\right)^2 \cos^2 \alpha} \qquad \textbf{(26)}$$

$$= \frac{(I_{//}^2 + I_{\perp}^2)}{(I_{\perp}^2)} = \frac{(I_{//}^2 + I_{\perp}^2)}{(I_{//}^2)} = \frac{1}{\left(\frac{1}{2}\right)} = 2 = 200\%$$

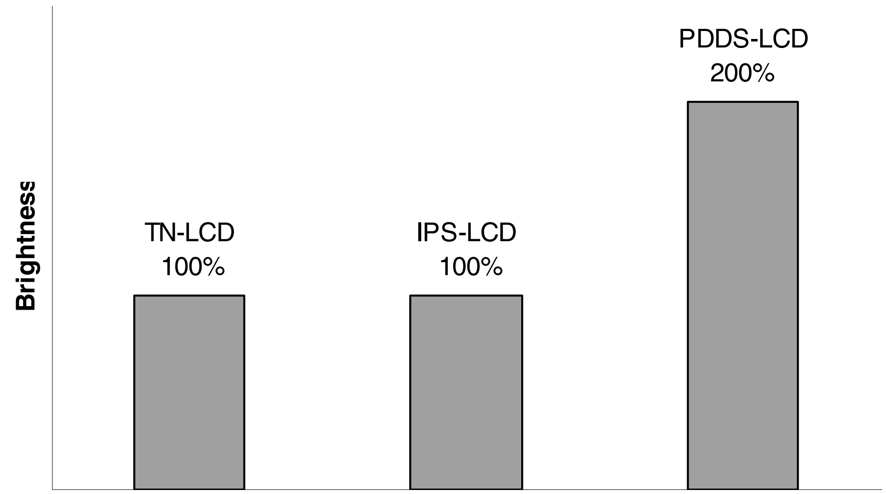


Figure 22: Brightness among Different Modes

The polarizer-free characteristic of the PDDS-LCD mode achieves 200% of the brightness of the TN-LCD and IPS-LCD modes. An illustrative comparison of brightness among the TN-LCD, IPS-LCD, and PDDS-LCD is shown in Figure 22.

6.2 Quantitative Analysis of Contrast

In the LCD, contrast was traditionally calculated as the largest brightness of the real "white" is divided by the lowest brightness of real "black" [12]. That is

$$C = \frac{Max\{B_1, B_2, ...B_i, ..., B_n\}}{Min\{B_{1,} B_2, ...B_i, ..., B_n\}} \qquad \textbf{(27)}$$

In Formula 27, C is the contrast ratio of the display, B_i is the brightness of the i^{th} pixel on the display, and n is the total number of sub-pixels consisting of the display.

Regardless of whether the multiplexing driving method or the Dual-Scan architecture is used, all sub-pixels across each row are connected together on one side of the glass substrate, and all sub-pixels in each column are connected together on the glass substrate of the opposite side. The rows are “addressed” in sequence and only one at a time. The voltages set on the columns correspond to the sub-pixel values in the row being addressed [4]. When an activated row and activated column intersect, the LC molecule inside the polymer will turn from the “off” state to the “on” state, and hence form an image element (sub-pixel) with different brightness on the display. The degree of brightness of an image element is from 0 to 255, which denotes the individual values of either color red, green, or blue. The brightness degree of an image element is determined by the LC molecule activation voltage, that is, the Voltage Drop (VD) “address” on a particular pixel. The VD of a particular pixel is discussed as follows.

As discussed previously: the disadvantages of the multiplexing driving method are that, if there are N rows in the large display, as the voltage cycles through them, the activated pixels in a given row will be at maximum contrast for only 1/N of the pulse time, since as mentioned previously: a $+V$ is applied to a row in sequence, and then a same value of $-V$ is applied to the column which needs to be switched. When the other rows are being “addressed”, during the rest of the time ((N-1)/N) when later rows are being addressed, the pixels in previous rows will experience a smaller net voltage (0-(-V)) than the activated rows do (V-(-V)) [13]. Therefore, the pixels never really maintain a full “on” or “off” voltage; they are always somewhere in between. The pixels in these rows will be receiving a smaller voltage than their previous rows do [13]. Since the image contrast of the LCD depends on how close the voltages of the rows are [2], the multiplexing driving used on LCDs results in imperfect contrast in the TN-LCD and IPS-LCD modes. Thus, the degree of multiplexing in LCD has an important influence on the contrast of the display. The LC molecules will respond to the average voltage applied to it over a certain period of time. Assuming that the LC molecule responds to voltage over one frame period, the average VD can be calculated by a pixel that is "on" and a pixel that is "off". Given a particular pixel, assume that other pixels in the same column have equal probabilities to be in the "on" state or the "off" state, which means, 50% of the pixels are in the "on" state and 50% of the pixels are in the "off" state. While a certain pixel is "on", the row containing the pixel must hold a voltage of +1 and its corresponding column must hold a voltage of -1, which results in a VD of 2 (by $1-(-1)=2$) between the row and its corresponding column. On the other hand, if a certain pixel is in the "off" state, the row containing the pixel must hold a voltage of 0, and its corresponding column must hold a voltage of -1, which results in a VD of 0 (by $0-(-1)=1$). When other $N-1$ rows are being driven, the row voltage is 0, and the column voltage changes between 0 and -1 as the other pixels in the column are addressed. This means it has an average voltage of $\frac{1}{2}$ during that time. Hence, when the pixel is in the "on" state, the Mean Voltage Drop (MVD) for N rows in the PDDS-LCD mode is calculated as Formula 28 [2]:

$$MVD_{on} = \frac{2+(N-1)/2}{N} = \frac{2\times 2+(N-1)}{2N} = \frac{(N+3)}{2N} \qquad \textbf{(28) [2]}$$

In Formula 28, MVD_{on} represents the Mean Voltage Drop (MVD) of each row in the case that a pixel is in the "on" state, and N represents the number of rows of the LCD [2].

When the pixel is in the "off" state, the Mean Voltage Drop (MVD) for N rows in the

PDDS-LCD mode is calculated as Formula 29 [2]:

$$MVD_{off} = \frac{1+(N-1)/2}{N} = \frac{1\times 2+(N-1)}{2N} = \frac{(N+1)}{2N} \qquad \textbf{(29) [2]}$$

In Formula 29, MVD_{off} represents the Mean Voltage Drop of each row in the case that a pixel is in the "off" state, and *N* represents the number of rows of the LCD [2].

MVD_{on}, and MVD_{off} represent the maximal percentile of light transmission and the minimal percentile of light transmission into the LCD, respectively, which is shown as Figure 23.

Since the voltage-brightness response curve of the LC molecule is typically not very steep shown as Figure 23, these voltages will not lead to as high of a difference in brightness as would be possible, if each pixel received either a full voltage of 2 or a voltage of 0 over the entire frame period. The ideal case can only be achieved when the response curve has a nearly infinite slope between the MVD_{on}, and the MVD_{off}. However, this is very difficult to achieve [2].

In PDDS-LCD mode, the contrast is defined as the ratio of brightness between "on" and "off" pixels. Based on the analysis of Mean Voltage Drop above, the ratio of brightness between "on" and "off" pixels can be represented by the Mean Voltage Drop of *N* rows in the PDDS-LCD mode in the case that the particular pixel is in the "on" state divided by the Mean Voltage Drop of *N* rows in the PDDS-LCD mode in the case that the particular pixel is in the "on" state. That is, the ratio of brightness between "on" and "off" pixels is equal to $\frac{MVD_{on}}{MVD_{off}}$. As shown in Figure 21, the ratio of brightness between "on" and “off” pixels specifies the slope ratio of the voltage-brightness curve. If the voltage-brightness curve has a near infinite slope between the average on and off voltages, the LCD achieves an ideal contrast.

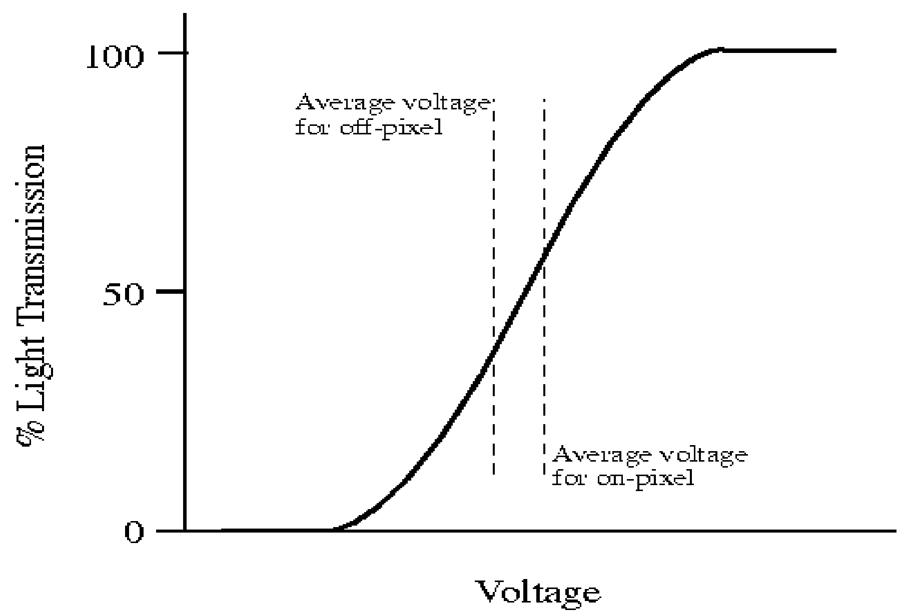


Figure 23 [2]: Range of Voltage (and Therefore Brightness) Drops with “on” and “off” Pixel

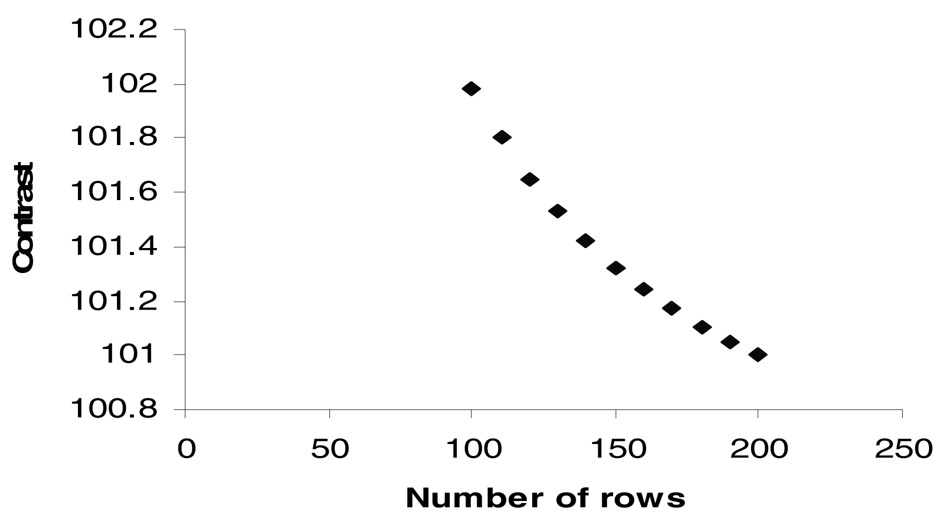


Figure 24: Correlation between Contrast and Number of Rows

Therefore, it is easy to present the contrast of the PDDS-LCD mode as formula 30

$$contrast = \frac{MVD_{on}}{MVD_{off}} = \frac{(\frac{N+3}{2N})}{(\frac{N+1}{2N})} = \frac{(N+3)}{(N+1)} \qquad \textbf{(30) [2]}$$

In Formula 30, N represents the number of rows. Therefore, contrast is a function of the number of rows, the more rows there are, the less the contrast of the LCD is. According to Formula 30, it is able to do the statistics of the data of contrasts by using the Dual-Scan architecture as well as using the multiplexing driving method in Table 1.

In Table 1, the number of rows is from 100 to 200. In Multiplexing Driving method, the number of rows on the substrate of one side of the LCD glass plate is 200, all 200 rows are on one side of the glass substrate, and 200 columns are on the opposite side of the glass substrate, while, in the Dual-Scan architecture the glass substrate on which the rows are placed in the LCD is divided into two sections and the rows corresponding to each separate section are connected to each other and then scanned simultaneously by an individual voltage. Thus, the number of rows of each separate display on one glass substrate decreases to 100 in the dual-scan architecture.

The correlation of contrast and the number of rows of LCDs is shown in Figure 24.

As Figure 24 illustrated, contrast of the display decreases with the increase of the number of rows in the LCD.

N	…	…	…	*100*	*101*	*102*	*103*	*104*	*105*	*106*
Contrast(E-2)	…	…	…	*101.98*	*101.96*	*101.94*	*101.92*	*101.90*	*101.89*	*101.87*
N	*107*	*108*	*109*	*110*	*111*	*112*	*113*	*114*	*115*	*116*
Contrast(E-2)	*101.85*	*101.83*	*101.82*	*101.80*	*101.79*	*101.77*	*101.75*	*101.74*	*101.72*	*101.71*
N	*117*	*118*	*119*	*120*	*121*	*122*	*123*	*124*	*125*	*126*
Contrast(E-2)	*101.69*	*101.68*	*101.67*	*101.65*	*101.64*	*101.63*	*101.61*	*101.60*	*101.59*	*101.57*
N	*127*	*128*	*129*	*130*	*131*	*132*	*133*	*134*	*135*	*136*
Contrast(E-2)	*101.56*	*101.55*	*101.54*	*101.53*	*101.52*	*101.50*	*101.49*	*101.48*	*101.47*	*101.46*
N	*137*	*138*	*139*	*140*	*141*	*142*	*143*	*144*	*145*	*146*
Contrast(E-2)	*101.45*	*101.44*	*101.43*	*101.42*	*101.41*	*101.40*	*101.38*	*101.38*	*101.37*	*101.36*
N	*147*	*148*	*149*	*150*	*151*	*152*	*153*	*154*	*155*	*156*
Contrast(E-2)	*101.35*	*101.34*	*101.33*	*101.32*	*101.32*	*101.31*	*101.30*	*101.29*	*101.28*	*101.27*
N	*157*	*158*	*159*	*160*	*161*	*162*	*163*	*164*	*165*	*166*
Contrast(E-2)	*101.27*	*101.26*	*101.25*	*101.24*	*101.23*	*101.23*	*101.22*	*101.21*	*101.20*	*101.20*
N	*167*	*168*	*169*	*170*	*171*	*172*	*173*	*174*	*175*	*176*
Contrast(E-2)	*101.19*	*101.18*	*101.18*	*101.17*	*101.16*	*101.16*	*101.15*	*101.14*	*101.14*	*101.13*
N	*177*	*178*	*179*	*180*	*181*	*182*	*183*	*184*	*185*	*186*
Contrast(E-2)	*101.12*	*101.12*	*101.11*	*101.10*	*101.10*	*101.09*	*101.09*	*101.08*	*101.08*	*101.07*
N	*187*	*188*	*189*	*190*	*191*	*192*	*193*	*194*	*195*	*196*
Contrast(E-2)	*101.06*	*101.06*	*101.05*	*101.05*	*101.04*	*101.04*	*101.03*	*101.03*	*101.02*	*101.02*
N	*197*	*198*	*199*	*200*	…	…	…	…	…	…
Contrast(E-2)	*101.01*	*101.01*	*101.00*	*101.00*	…	…	…	…	…	…

Table 1: Contrast v.s. Number of Rows

As discussed above, if N rows are on one side of the glass substrate and N columns are on the opposite side of the glass substrate, as well as the multiplexing driving method is employed in the TN-LCD and IPS-LCD modes, the number of rows on one side of the LCD glass substrate is counted as N. However, in the PDDS-LCD mode, since the Dual-Scan architecture is employed, the glass substrate on which the rows are placed in the LCD is divided into two sections, and then the rows corresponding to each separate section are connected to each other, and are scanned simultaneously by an individual voltage. By employing the Dual-Scan architecture, the number of rows of each separate display of one glass substrate is decreased to $\frac{N}{2}$. Then, the ratio of the contrast of the PDDS-LCD mode to the contrast of the TN-LCD and IPS-LCD modes is

$$\frac{\left(\frac{\frac{N}{2}+3}{\frac{N}{2}+1}\right)}{\left(\frac{N+3}{N+1}\right)}\times 100\% = \frac{\left(\frac{N+6}{N+2}\right)}{\left(\frac{N+3}{N+1}\right)}\times 100\% \geq 1\times 100\% \geq 100\% \qquad \textbf{(31)}$$

As showed in inequality 31, the ratio of the contrast of the PDDS-LCD mode to the contrast of the TN-LCD and IPS-LCD modes is more than 100%.

If 200 rows are on one side of the glass substrate and the other 200 columns are on the opposite side of the glass substrate, and the multiplexing driving method is employed in the TN-LCD and IPS-LCD modes, the number of rows on one side of the LCD glass substrate is then counted as 200. However, in the PDDS-LCD mode, the Dual-Scan architecture is employed, the glass substrate on which the rows are placed in the LCD is divided into two sections, and then the rows corresponding to each separate section are connected to each other, and are scanned simultaneously by an individual voltage. By employing the Dual-Scan architecture, the number of rows of each separate display of one glass substrate is decreased to 100. Hence, the ratio of the contrast of the PDDS-LCD mode to the contrast of the TN-LCD and IPS-LCD modes is

$$\frac{\frac{200+6}{200+2}}{\frac{200+3}{200+1}}\times 100\% = \frac{1.02}{1.01}\times 100\% \approx 1.01\times 100\% \ \approx 101\% \geq 100\% \qquad \textbf{(32)}$$

A comparison of contrasts among the TN-LCD, IPS-LCD and PDDS-LCD modes is shown approximately in Figure 25.

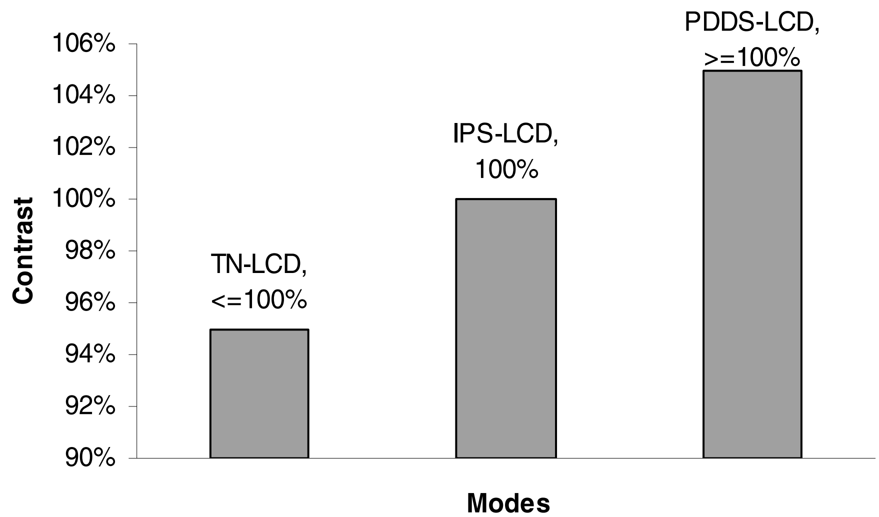


Figure 25: Contrast among Different Modes

As illustrated in Figure 25, among the three LCD modes, the PDDS-LCD mode obtains the highest contrast, which is more than 100%. The IPS-LCD mode has 100% contrast. The TN-LCD mode has the lowest contrast, which is lower than 100% contrast. The reasons behind this are that (1) the characteristic of Dual-Scan architecture of the PDDS-LCD mode increases the contrast; (2) in the IPS-LCD mode, LC molecules are always lying parallel to the glass substrate if no voltage is applied. When a voltage is applied in that glass substrate, LC molecules rotate according to how much voltage is applied while remaining parallel to the glass substrate [11], which has a 100% contrast;

and (3) the contrast in the TN-LCD mode is reduced because LC molecules are not completely perpendicular even with a full voltage applied [11] as mentioned previously.

7. Conclusion

In this thesis, the Polymer-Dispersed Dual-Scan Liquid Crystal Display (PDDS-LCD) mode has been proposed and a quantitative modeling and analysis method has been developed in order to justify the efficiency and effectiveness of the proposed LCD mode. The Polymer-Dispersed technology [2] has been employed to achieve a dramatically improved brightness but with limitation on improvement of image contrast. In order to address and resolve this problem, the Dual-Scan architecture [17] has been employed. For a comparative study with respect to the brightness and contrast of the TN-LCD and IPS-LCD modes, a quantitative analysis of Polymer-Dispersed technology has been conducted to demonstrate the effectiveness of its brightness and contrast. The quantitative analysis along with a software simulation has shown and validated the technological benefits of the proposed PDDS-LCD in terms of its structural simplicity as well as its image quality. The validation results have revealed that the PDDS-LCD mode successfully achieves up to 200% increase in brightness on the display side and contrast is also improved, compared to the TN-LCD and IPS-LCD modes.

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GLOSSARY

LCDs	Liquid Crystal Displays, which is a thin, flat display device made up of any number of color or monochrome pixels arrayed in front of a light source or reflector.
PDDS-LCD	Polymer-Dispersed Dual-Scan Liquid Crystal Display
LC	Liquid Crystal, which is composed of moderate size organic molecule, tends to be elongated and shaped like a cigar and highly exotic shapes as well. Because of their elongated shape, the molecules can exhibit orientational order under appropriate, such that all the axes line up in a particular direction. In consequence, the bulk order has profound influences on the way light and electricity behaves in the material.
TN-LCD	The Twisted Nematic Liquid Crystal Display mode
IPS-LCD	The In-Plane-Switch Liquid Crystal Display mode
ITO	Indium Tin Oxide
RGB	Red-Green-Blue
PVA	Polyvinyl Alcohol
VD	The Voltage Drop, a parameter used to measure the falling of the voltage between any of two points
MVD	The Mean Voltage Drop, a parameter used to represent the mean of among a certain number of VD between each row and its corresponding column

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ABSTRACT:

Liquid Crystal Display (LCD) is a key technology in multimedia applications. Improving LCD image quality is one of the most important issues in the research and development of LCDs. Brightness and contrast are two major factors in determining the image quality of LCDs. The existing Twisted Nematic Liquid Crystal Display (TN-LCD) and In-Plane-Switch Liquid Crystal Display (IPS-LCD) LCD modes have demonstrated effectiveness in managing brightness and contrast. Furthermore, until now, there has been little adequate research for quantitative analysis of brightness and contrast for LCD modes.

In this thesis, an analytical LCD mode, the Polymer-Dispersed Dual-Scan Liquid Crystal Display (PDDS-LCD) mode, is proposed. In the proposed PDDS-LCD mode, the Polymer-Dispersed technology [2] is employed to achieve a higher and more effective brightness. The employment of Polymer-Dispersed technology helps achieve a dramatically improved brightness but with limitation on improvement of image contrast. In order to address and resolve this problem, the Dual-Scan architecture [17] is employed. For a comparative study with respect to the brightness and contrast of the TN-LCD and IPS-LCD modes, a quantitative analysis of Polymer-Dispersed technology has been conducted to demonstrate the effectiveness of brightness and contrast. The quantitative analysis along with a software simulation has shown and validated the technological benefits in term of structural simplicity as well as image quality.

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