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Understanding Crosstalk in Stereoscopic Displays

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Abstract— **Crosstalk is a critical factor determining the image quality of stereoscopic displays. Also known as ghosting or leakage, high levels of crosstalk can make stereoscopic images hard to fuse and lack fidelity; hence it is important to achieve low levels of crosstalk in the development of high-quality stereoscopic displays. In the wider academic literature, the terms crosstalk, ghosting and leakage are often used interchangeably but it would be helpful to have unambiguous descriptive and mathematical definitions of these terms. The paper reviews a wide range of mechanisms by which crosstalk occurs in various stereoscopic displays, including: time-sequential on PDPs and CRTs (phosphor afterglow, shutter timing, shutter efficiency), MicroPol LCDs (polarization quality, viewing angle), time-sequential on LCDs (pixel response rate, update method, shutter timing & efficiency), autostereoscopic (inter-zone crosstalk), polarised projection (quality of polarisers and screens), anaglyph (spectral quality of glasses and displays). Crosstalk reduction and crosstalk cancellation are also discussed along with methods of measuring and characterising crosstalk.**

Keywords - crosstalk; ghosting; leakage; LCD; PDP; CRT; DLP; polarised; anaglyph, stereoscopic, autostereoscopic.

I. INTRODUCTION

This paper provides an overview of the concepts of crosstalk (sometimes 'cross talk', or 'cross-talk' [37]) in stereoscopic 3D displays, including a review of the terminology relating to stereoscopic crosstalk as it is in common usage, a review of the sources of ghosting in a selection of commonly used stereoscopic displays, and a discussion of methods of measuring, characterising and reducing stereoscopic crosstalk.

In its simplest form crosstalk in stereoscopic displays is the leakage of the left image channel into the right eye view and vice versa.

II. TERMINOLOGY AND DEFINITIONS

The terms crosstalk and ghosting are often used interchangeably in some of the published literature and unfortunately very few publications actually provide a descriptive or mathematical definition of these terms. Unfortunately when definitions are provided they are sometimes contradictory:

Lipton [1] provides the following definitions:

Crosstalk: "Incomplete isolation of the left and right image channels so that one leaks (leakage) or bleeds into the other. Looks like a double exposure. Crosstalk is a physical entity and can be objectively measured, whereas ghosting is a subjective term."

Ghosting: "The perception of crosstalk is called ghosting."

Huang, et al [2] provide the following definitions:

System Crosstalk: "for the left-eye case … can be defined as:

$$\text{System crosstalk (left eye)} = \beta_2 / \alpha_1 \quad (1)$$

describing the degree of the unexpected leaking image from the other eye." Where: "α_1 describes the percentage part of the left-eye image observed at the left eye position", and "β_2 describes the percentage part of the right-eye image leaked to the left-eye position."

Viewer Crosstalk: "means the crosstalk perceived by the viewer [7]." It is "defined as the ratio of the luminance of unwanted ghost image, which leaks from the image for the other eye, to the luminance of the correct information received by the viewer's eyes. The viewer crosstalk for the viewer's left eye can be defined as:

$$\text{Viewer crosstalk} = \mathbf{B}\,\beta_2 / \mathbf{A}\,\alpha_1 \text{ ''} \quad (2)$$

Where: **A** is the luminance of a particular point in the left eye image, and **B** is the luminance of the same corresponding point (same x,y location) in the right-eye image.

Therefore, System Crosstalk is independent of the content, whereas Viewer Crosstalk varies depending upon the content.

There is some similarity between Lipton's "Crosstalk and Ghosting" vs. Huang's "System Crosstalk and Viewer Crosstalk" definitions but there are still some notable differences, specifically "ghosting" includes any perception issues, whereas Huang's "viewer crosstalk" only considers co-location image contrast [7] and not the amount of disparity [6].

Stevens [34] provides a slightly different definition for viewer crosstalk: "the ratio of luminance of the 'wrong' image to the luminance of the 'correct' image as seen by the observer. It will be a function of the image contrast and the disparity."

This paper will not provide recommendations on terminology usage, but perhaps this can happen after further literature search and industry-wide debate.

Three other terms which have been used when referring to crosstalk are:

Leakage: in very general terms this refers to the raw amount of light which leaks from one channel to another – but it is usually undefined in the literature.

Extinction and extinction ratio: usually refer to the ratio between the intensity of the intended image as compared with the intensity of the unintended image – but it is usually not specifically defined in the stereoscopic literature.

3D contrast: the inverse of 3D crosstalk [32].

A. Mathematical Definitions

In addition to equations (1) and (2) provided above, a selection of other mathematical definitions appear in the literature:

Liou, et al [22] provides the following equations:

$$CL = (BW - BB) / (WB - BB), \text{ and} \quad (3)$$
$$CR = (WB - BB) / (BW - BB) \quad (4)$$

Where: WB = a video stream with all white as left-eye images, and all-black as right-eye images, BW = a video stream with all-black as left-eye images and all-black as right eye images, BB = a video stream with all-black for both left and right eyes (i.e. the black level of the display), and CL and CR = the crosstalk experienced by the left eye and the right eye.

Pala, et al [10] and Boher, et al [32] use something very similar to the above but with different variable names.

Woods and Harris [40] and Hong, et al [31] used a simpler equation:

$$\text{Crosstalk (\%)} = \text{leakage} / \text{signal} \times 100 \quad (5)$$

Shestak, et al [21] provide equations for dark crosstalk, light crosstalk, and grey-to-grey crosstalk specifically relating to crosstalk in time-sequential 3D on LCDs:

$$\text{Dark crosstalk } C^{dark} = (W'_2 - W_2) / (W_1 - W_2) \quad (6)$$
$$\text{Light crosstalk } C^{light} = (W'_1 - W_1) / (W_2 - W_1) \quad (7)$$

Where: W_1 and W_2 are the original desired luminance for points in the left and right eye view (W_1 is the lower of the two luminances), W'_1 is the displayed luminance affected by crosstalk which brightens the image, and W'_2 is the displayed luminance affected by crosstalk which darkens the image. Grey-to-grey crosstalk is the matrix of values of C for all grey level combinations for W_1 and W_2.

Additionally, Boher, et al [32] define 3D contrast as:

$$C_L = 1/\chi_L,\ C_R = 1/\chi_R \text{ and } C^{3D} = (C_R \times C_L)^{0.5} \quad (8,9,10)$$

Where: C_L and C_R are 3D contrast for the left and right eyes as viewed through the left and right filters, χ_L and χ_R is the 3D crosstalk for left and right eyes, and C^{3D} is the combined 3D contrast for both eyes. Note that the variable name C is used for contrast in [32] whereas C is used for Crosstalk in most other stereoscopic papers.

III. Perception of Crosstalk

The perception of crosstalk in stereoscopic displays has been studied widely [6][7][8][9][10][11]. It is widely acknowledged that the presence of high levels of crosstalk in a stereoscopic display are detrimental. The effects of crosstalk in an image include: ghosting and loss of contrast, loss of 3D effect and depth resolution, and viewer discomfort [34].

The visibility of crosstalk (ghosting) increases with increasing contrast and increasing binocular parallax of the image [6][9][21] (see Fig. 1). For example, a stereoscopic image with high-contrast will exhibit more ghosting on a particular stereoscopic display than will an image with low contrast.

The literature provides various advice on the amounts of crosstalk that are acceptable and unacceptable – but unfortunately not all the advice agree. Some examples include [36]: "crosstalk between 2 and 6% significantly affected image quality and visual comfort", "crosstalk should be as low as 0.3%" [6], "crosstalk. … visibility threshold of about 1 to 2%", "crosstalk level of about 5% is sufficient to induce visual discomfort in half of the population" [8].

IV. Measurement of Crosstalk

Two methods exist for the measurement of crosstalk:

A. Optical Sensors

An optical measurement device (such as a photometer or a radiometer) can be used to measure crosstalk. Examples of sensors that have been used to measure crosstalk include: Integrated Photomatrix Inc. IPL10530 DAL photo-diode [12], Ocean Optics USB2000 spectroradiometer [39], Minolta CS1000 spectroradiometer [31][34], Minolta CS-100 spot chroma meter [7][22], and Eldim EZContrastMS [32]. Many other devices can also be used for this purpose. It is important to note that for any optical sensors that are used, consideration needs to be given to how well the spectral sensitivity of the sensors match the spectral sensitivity of the human eye (Fig. 2).

Traditionally, crosstalk is measured by displaying full-black and full-white in opposing eye-channels of the display and using an optical sensor to measure the amount of leakage between channels. For example, the optical sensor is placed at the left eye position (either behind the left eye of 3D glasses, or in the left eye viewing zone for an autostereoscopic display)

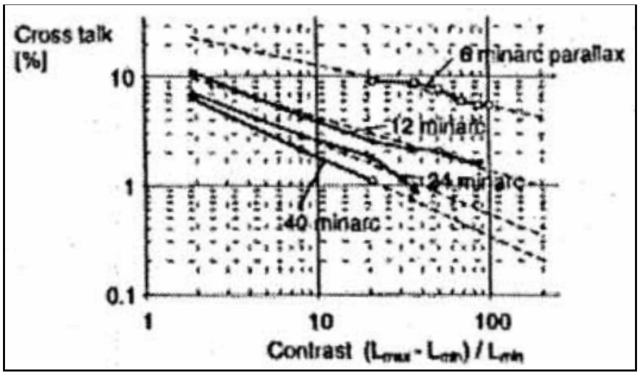

Figure 1. The threshold of visibility of crosstalk for different amounts of disparity and image contrast ratio. [6]

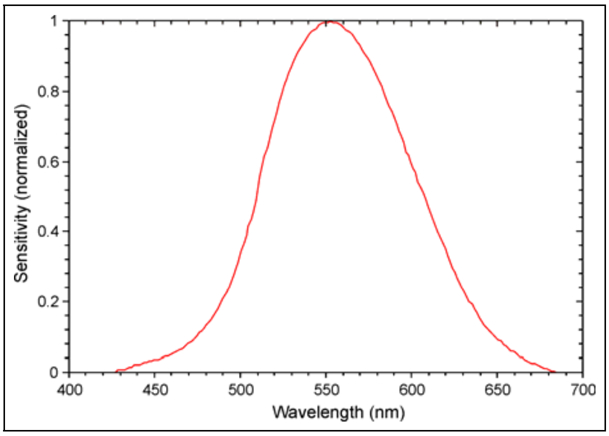

Figure 2. CIE 1931 photopic human eye spectral response. [3]

and measurements are taken for the four cross-combinations of full-white and full-black in the left and right eye-channels. An additional reading is also taken with the display in the off state. These readings can then be used in the crosstalk equations described above. This metric can be called black-and-white crosstalk and this metric is often used because maximum crosstalk occurs when the pixels in one eye-channel are full-black and the same pixels in the opposite eye-channel are full-white.

Another metric called grey-to-grey crosstalk was recently proposed for measuring crosstalk in time-sequential 3D LCDs [21]. Crosstalk occurs differently in time-sequential 3D LCDs than it does in other displays, which is related to the way that pixels change from one grey level to another and the pixel response rate [16] for LCDs varying with different grey level changes. Grey-to-grey crosstalk is measured for various left and right grey level combinations and a more complex analysis of crosstalk is performed [21].

B. *Visual Measurement Charts*

Visual measurement charts provide a very quick and effective way of evaluating crosstalk in a stereoscopic display without the need for optical test equipment. Two examples of such charts are shown in Fig. 3 and 4. The method of using the charts is to display the left and right panels of the chart in the left and right channels of the stereoscopic display. The user then visually compares the amount of crosstalk visible on screen for each eye separately (in nominated areas of the chart) against a scaled grey level ramp.

Unfortunately there are some limitations of this method (a) the gamma curve of the monitor should be calibrated using an appropriate sensor (such as the Spyder 3 from Datacolor), (b) the chart does not account for the non-zero black level of some monitors (e.g. LCDs), and (c) crosstalk can be different in different parts of the screen (these charts only measure crosstalk in relatively small portions of the screen – although this can be easily addressed with changes or multiple versions of the charts).

Due to the limitations of the visual measurement charts, appropriate electro-optic tools should be used when high accuracy crosstalk data is needed.

V. CROSSTALK MECHANISMS

There are various mechanisms by which crosstalk occurs in stereoscopic displays and these mechanisms vary between different stereoscopic display technologies.

The sections below summarise the important performance attributes for various stereoscopic display technologies and the mechanisms by which crosstalk occurs in each. This list of 3D displays is not intended to be exhaustive – people are incredibly inventive and there are literally hundreds of different stereoscopic display technologies and it is not possible to discuss all stereoscopic display technologies in one short paper – but it will give the reader information about the contributors to crosstalk in a selection of common stereoscopic displays and hopefully provide clues as to the crosstalk mechanisms in other displays not specifically discussed.

It is also important to note that crosstalk can also occur during the stereoscopic image acquisition stage (e.g. using a NuView 3D lens), and also during stereoscopic image manipulation or storage (e.g. saving a row-interleaved or anaglyph 3D image in JPEG format). This paper assumes that steps have been taken to avoid such sources of crosstalk.

A. *Time-Sequential 3D using LCS 3D Glasses*

There are a wide range of stereoscopic display systems which make use of the time-sequential or time-multiplexed 3D display method and all of these invariably use active shutter glasses or Liquid Crystal Shutter (LCS) 3D glasses to gate the appropriate image to each eye. The properties of the liquid crystal shutter are also a key determinant in the amount of crosstalk present with those time-sequential 3D displays which use LCS 3D glasses.

The methods by which crosstalk occurs in systems using LCS 3D glasses are:

- the optical performance of the liquid crystal cells (namely: the amount of transmission in the ‘opaque’ state, the rise time, the fall time, and the amount of transmission in the ‘clear’ state – see Fig. 5),
- the relative timing (synchronisation) of the glasses with respect to the display,
- the angle of view through the liquid crystal cells (optical performance of the cells usually falls off with viewing angles which are off perpendicular), and
- the temporal performance of the particular display being used (and how this interacts with the temporal performance of the shutters).

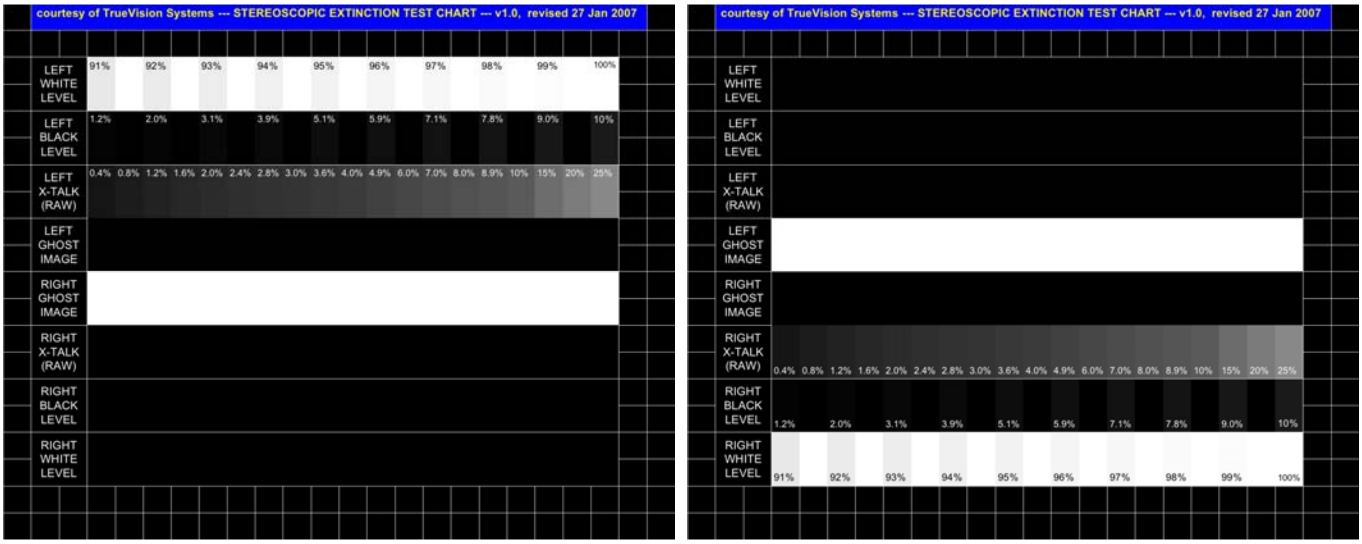

Figure 3. Crosstalk measurement test chart designed by Mike Weissman. [4]

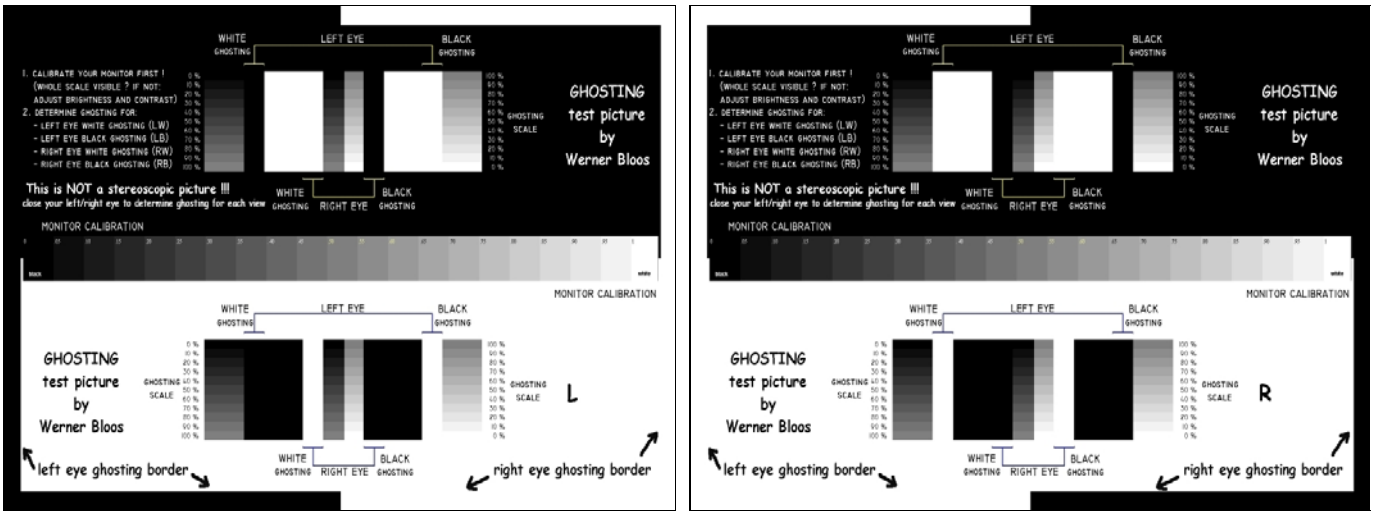

Figure 4. Crosstalk measurement test chart designed by Werner Bloos. [5]

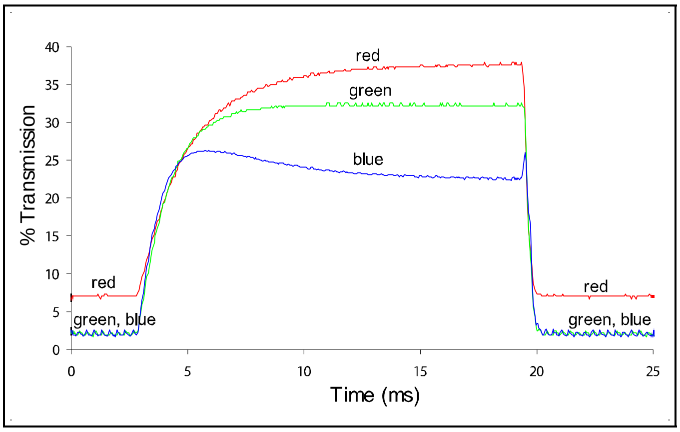

Figure 5. The transmission vs. time response of an example pair of LCS 3D glasses at red, green and blue wavelengths. [12]

With regards to the last bullet point, some displays are impulse-type displays, some are hold-type displays and others are a mix of the two [23]. The image update method of a display describes the way in which the screen is updated from one image to another – in some displays the image is scanned from the top to bottom (e.g. CRTs [12] and LCDs [16]), whereas other displays update all pixels on the screen at the same time (e.g. DLPs [24] and PDPs [15]).

B. *Time-Sequential 3D on CRTs*

CRT (Cathode Ray Tube) displays are an impulse-type display and the image is updated from top to bottom as the display is scanned by the electron beam – the phosphors in the screen emit light as they are hit by the electron beam.

With time-sequential 3D on a CRT, the important contributors to crosstalk [12][13][14] are:

- the performance of the liquid crystal cells (see Section V-A),

- the amount of phosphor persistence (the time that it takes for the phosphors to stop glowing after they have been energised – see Fig. 6),
- the timing of the shuttering of the glasses with respect to the display of images on the screen (see Fig. 7), and
- the x-y position on the screen (the bottom of the screen will exhibit more ghosting than the top of the screen due to the way that the electron beam scans the display from top to bottom - see Fig. 8).

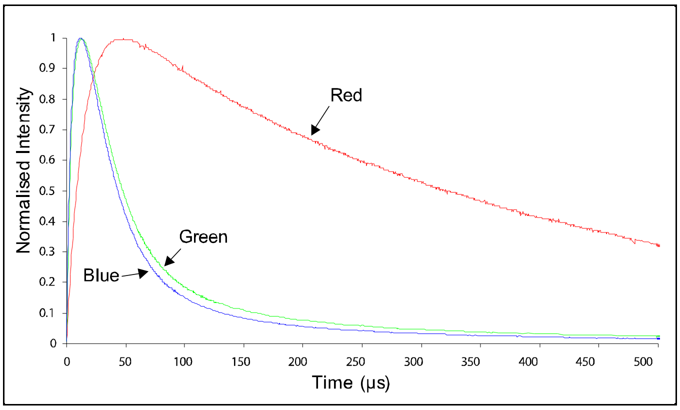

Figure 6. Phosphor intensity vs. time response for the three phosphors of a typical CRT display. [12]

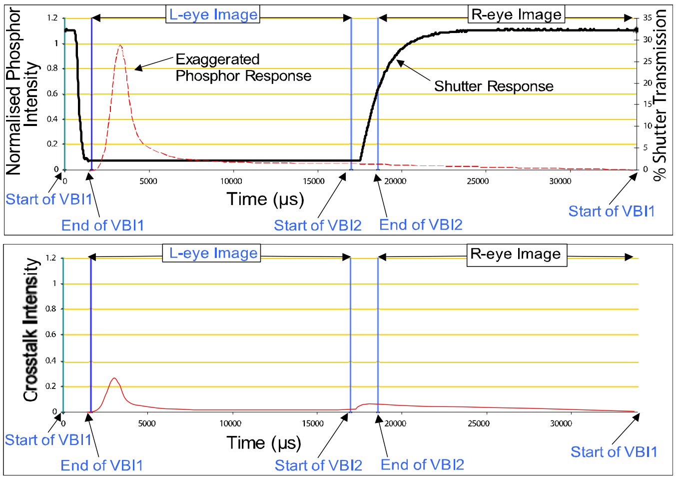

Figure 7. Illustration of crosstalk on a CRT (with exaggerated phosphor response for illustrative purposes). Top: phosphor response and shutter response. Bottom: multiplication of phosphor response by the shutter response to give the amount of crosstalk. [12]

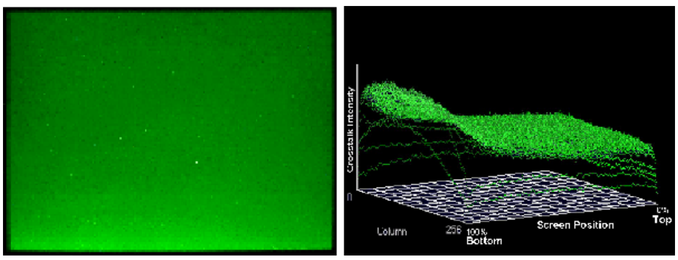

Figure 8. Illustration of spatial variation on crosstalk on a CRT with increased crosstalk at the bottom of the screen. Left: screen image. Right: histogram of measured CRT crosstalk. [12]

C. Time-Sequential 3D on PDPs

Plasma Display Panels (PDPs) generate light using phosphors, but differently to CRTs the phosphors can be energised up to 10 times per frame (see Fig. 9) and the all pixels on the display can be energised at once. Different grey levels are achieved for each pixel by firing or not firing the phosphors for each pixel in none, some, or all of the 10 sub-frames per frame. This makes PDP a cross between an impulse-type display and a hold-type display.

With time-sequential 3D on a PDP, the important contributors to crosstalk are:

- the performance of the liquid crystal cells in the shutter glasses (see Section V-A),
- the amount of phosphor persistence (the time that it takes for the phosphors to stop glowing after they have been energised – see Fig. 9),
- the timing of the shuttering of the glasses with respect to the display of images on the screen (see Fig. 10 and 11), and
- the particular grey level value of a displayed pixel (and therefore which sub-frames are fired - a sub-frame fired immediately before the transition point will dump more light into the following frame dur to phosphor persistence than for a sub-frame which is fired earlier whose phosphor persistence will have had more time to decay before the next frame - see Fig. 10).

Crosstalk does not vary with screen position on PDPs except where the viewing angle through the LCS glasses might be different for viewing different parts of the screen.

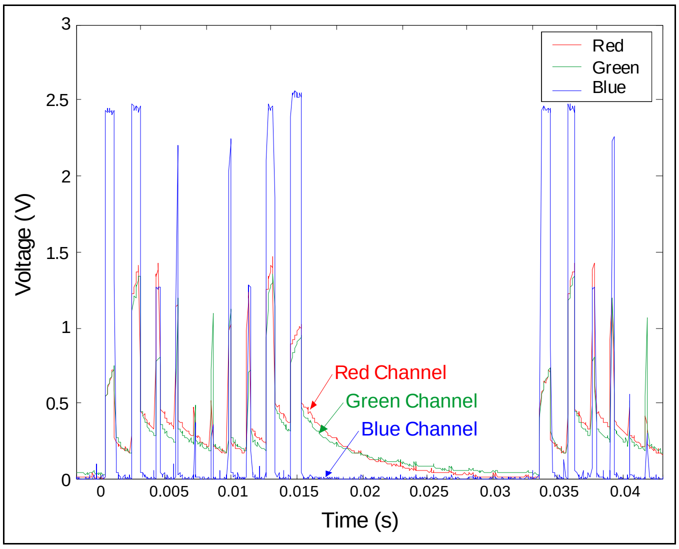

Figure 9. The time-domain light output of an example plasma display (for alternate frames of 100% red, green and blue vs. black). The vertical axis is brightness of the each of the color channels as measured in volts by the photo sensor, and the horizontal axis is time (seconds). [15]

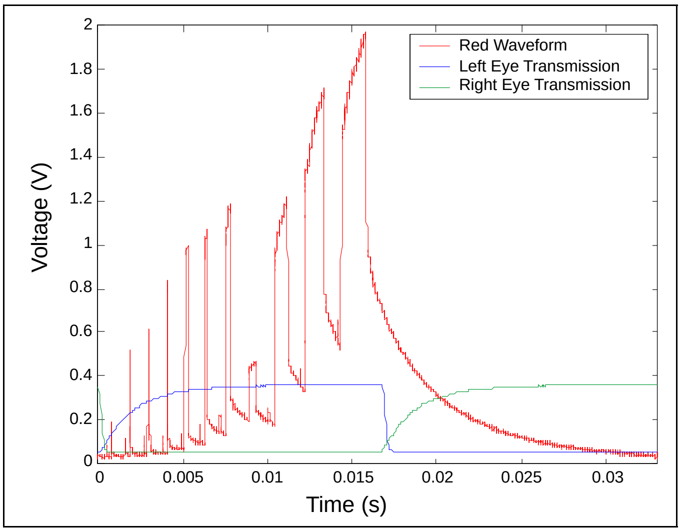

Figure 10. Diagram showing the LCS 3D glasses transmission states for both eyes and the time-domain light output for a red frame (followed by a black frame) for a different example PDP. The vertical axis is brightness of the each of the color channels as measured in volts by the photo sensor. [15]

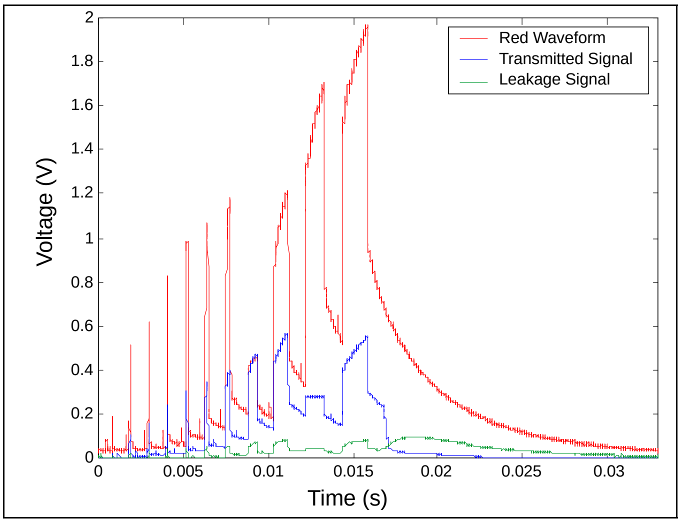

Figure 11. Diagram showing the original red waveform of an example PDP monitor (red) (from Fig. 10), the transmitted signal to the left eye of the LCS glasses (blue), and the crosstalk signal to the right eye through the LCS glasses (green). [15]

D. Time-Sequential 3D on LCDs

Liquid Crystal Displays (LCDs) generate an image by the use of a backlight mounted behind an LCD panel containing an array of individually addressable cells (usually three cells for each pixel – one for each of red, green and blue colour primaries). Each cell gates the light from the backlight, either passing light, blocking light or somewhere in between for different grey levels. Traditionally the backlight in LCDs has based on a Cold Cathode Fluorescent Lamp (CCFL) but LEDs are now also being used. The light source for an LCD projector is usually a halogen lamp. Regular LCDs are a hold-type display meaning that they output light for the entire frame period. Technologies such as Black Frame Insertion (BFI) and modulated backlight are also used with LCDs [17].

Until recently it was not possible to use the time-sequential 3D viewing method with LCDs (mostly due to the image update method – see Fig. 12), but recently new products have been released which allow the successful use of the time-sequential 3D method on LCDs (using either a modified image update method (for example see Fig. 13), BFI, an increased frame rate, and/or a modulated backlight [16][17][18][19][20]).

With time-sequential 3D on an LCD, the important contributors to crosstalk are:

- the performance of the liquid crystal cells in the shutter glasses (see Section V-A),
- the specific timing of the image update method on the screen (see Fig. 12 and 13) (including the effects of BFI, increased frame rate, and/or modulated backlight),
- the pixel response rate of the LCD (black-to-white, white-to-black, and grey-to-grey),
- the timing of the shuttering of the glasses with respect to

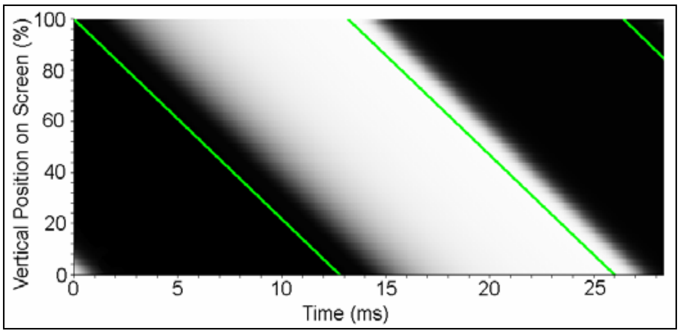

Figure 12. Time domain response of a regular LCD monitor with a 4% vertical blanking interval between alternating black and white frames. [16]

(a)

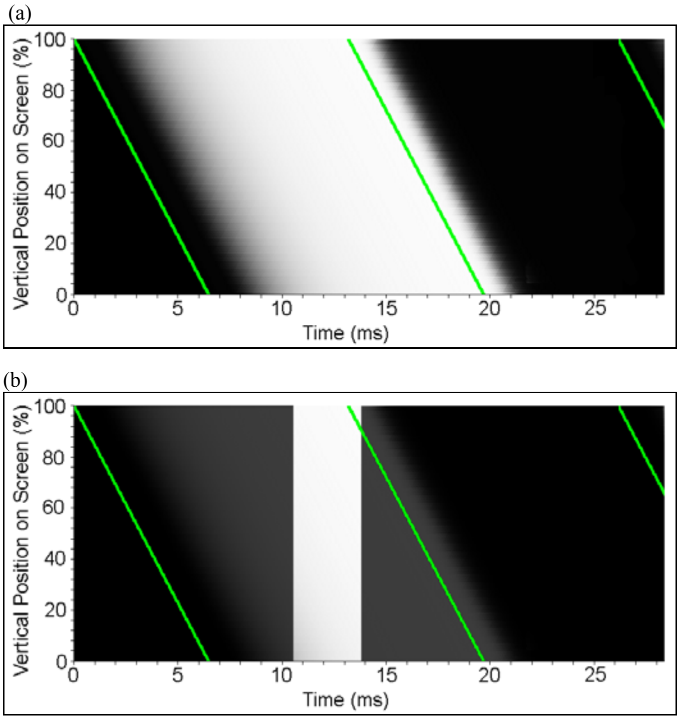

Figure 13. (a) Time domain response of a simulated LCD monitor with a fast addressing rate and fast pixel response rate and (b) the same being used with reduced duty cycle active shutter glasses (the response rate of shutters are not shown). [16]

the display of images on the screen (see Fig. 13) (including the duty cycle of the shutters),
- the particular grey level value of a displayed pixel, and
- the x-y position on the screen (depending upon shutter timing, the top and bottom of the screen may exhibit more crosstalk than the middle of the screen – see Fig. 13) [16].

E. Time-Sequential 3D on DLPs

DLP projectors and DLP rear-projection TVs work by shining an illuminator (e.g. a metal halide arc lamp or LEDs) onto a DMD (Digital Micro-Mirror Device – an array of tiny mirrors which can be individually commanded to rotate ±12 degrees). The reflection off the DMD is sent through a lens and focused on a screen and each mirror on the DMD corresponds to one pixel on the screen. In single-chip DLP projectors a colour-sequential technique is used to achieve a full-colour image (see Fig. 14) [24]. DLPs operate like a hold-type display - except that grey levels are achieved by a duty cycle process and it is possible to introduce blanking intervals.

DLPs have very good performance characteristics for time-sequential 3D display – in essence there is no crosstalk introduced by the actual DLP display itself. This is due to two key points: there is no phosphor decay (the DMD mirrors can switch completely from one state to another in ~2μs) and the entire image changes from one frame to the next at effectively the same time (hence crosstalk does not vary with screen position on DLPs except where the viewing angle through the LCS glasses might be different for viewing different parts of the screen). Ordinarily the only crosstalk present with time-sequential 3D on DLP is due to the LCS glasses.

The important contributors to crosstalk for time-sequential 3D on DLP are:
- the performance of the liquid crystal cells in the shutter glasses (see Section V-A), and
- the timing of the shuttering of the glasses with respect to the display of images on the screen (see Fig. 14).

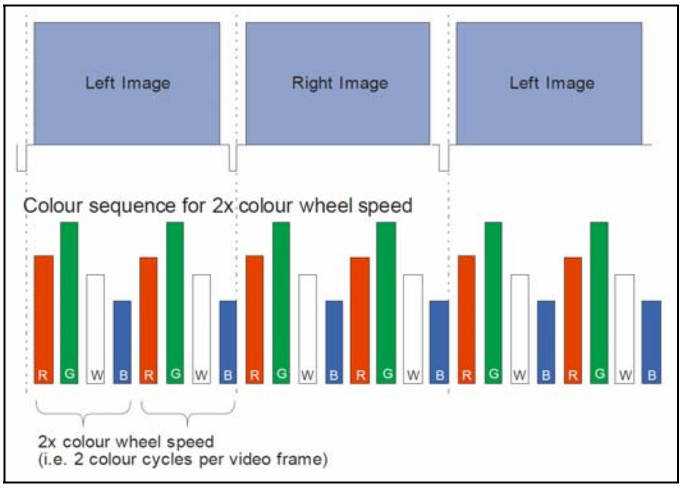

Figure 14. Illustration of a 60Hz time-sequential 3D video signal shown on an example 3D-Ready single-chip DLP projector with a 2x colour wheel. [24]

F. Polarised 3D Projection

The conceptually simplest method of achieving polarised 3D projection involves the use of two projectors, a polariser fitted to the front lens of each projector, a silvered screen, and polarised 3D glasses for the audience. The polarisers can either be circular polarisers or linear polarisers.

With dual-projector polarised 3D projection the factors which affect crosstalk are:
- the optical quality of the polarisers (optical performance of example linear and circular polarisers are shown in Fig. 15 and 16),
- the optical quality of the particular projection screen used (different screen materials have different polarised light performance [27], and front projection screens have difference polarisation performance characteristics to rear-projection screens), and
- incorrect orientation of the coding or decoding polarisers (linear polarisers must be crossed to block light and be parallel to pass light – circular polarisers have matching left-hand and right-hand versions but the orientation of the rear linear layer must match for optimal performance).

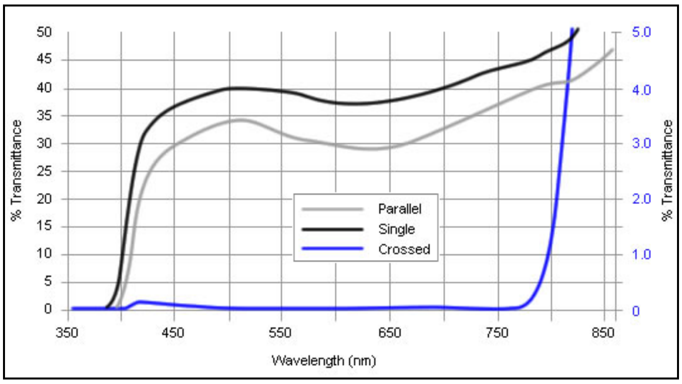

Figure 15. Spectral response of single, parallel and crossed linear polarisers. [25]

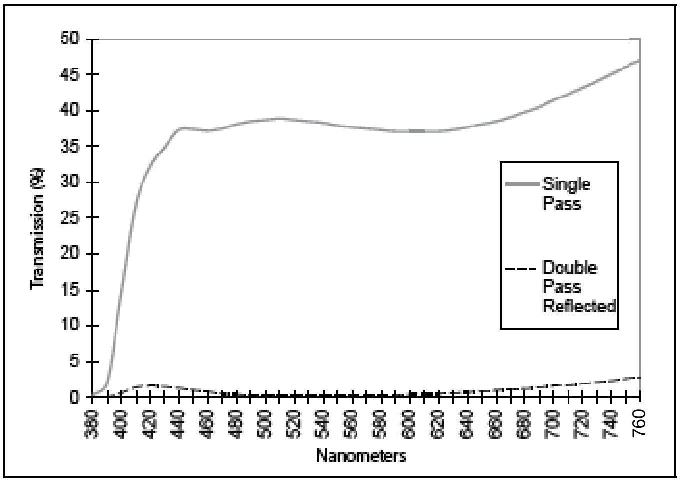

Figure 16. Spectral response of single and 'crossed' circular polarisers. [26]

Polarised 3D projection can also be achieved time-sequentially with the use of a polarisation modulator (as used by Real D, NuVision, and DepthQ) or a circular polarization filter wheel (as used by MasterImage). In this case there are two additional factors which can affect crosstalk [18][28], namely:

- the phase of the polarisation modulator with respect to the display, and
- the optical quality of the polarisation modulator.

G. Micro-Polarised 3D LCDs

Micro-polarised (also known as micro-pol, µPol, or X-Pol) 3D LCD monitors work by the application of a special optical filter to the front of a conventional LCD panel in order to polarise odd numbered rows of pixels with one polarisation state and the even numbered rows with the opposite polarisation state (see Fig. 17).

With a micro-polarised 3D LCD, the factors which contribute to crosstalk are:

- the optical quality of the micro-polariser film (and hence the quality of the two polarisation states),
- the accuracy of the alignment of the micro-polariser 'strips' to the rows of pixels on the display,
- the pitch of the micro-polariser 'strips' relative to the pitch of rows of pixels on the display (which will determine the optimum viewing distance),
- the presence (or absence) of a black mask between micro-polariser 'strips' - the presence of black mask improves the size of the viewing zones but at the sacrifice of screen brightness,
- the x-y position on the screen (different areas of the screen may exhibit more crosstalk than others),
- the viewing position of the observer (most current micro-pol monitors are highly sensitive to vertical viewing position, and also sensitive to the viewing distance from the monitor – see Fig. 18) [32],
- the thickness of the front glass layer, and
- the orientation [31], optical quality, and optical match of the polarised 3D glasses (with respect to the output polarisation of the display).

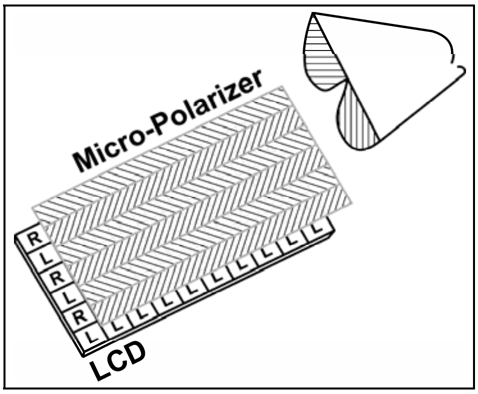

Figure 17. The optical layout of a micro-polarised 3-D LCD. A micro-polariser layer over the front of the LCD polarises alternate rows of pixels into two different polarization states. [29]

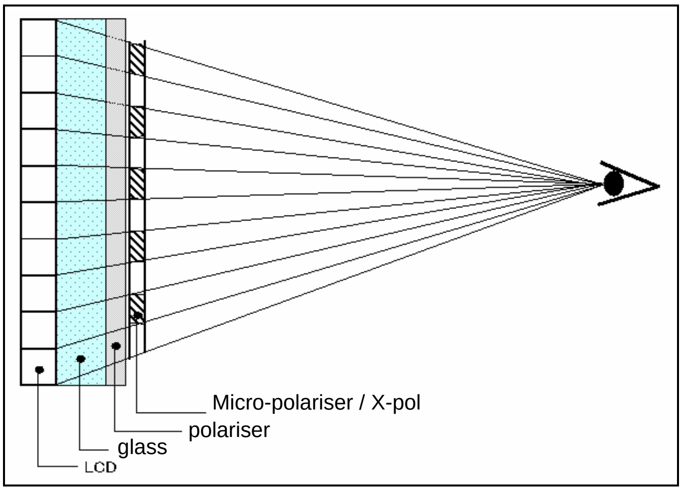

Figure 18. A side view of micro-polariser film fitted to an LCD monitor illustrating the reason for viewing location sensitivity of the display. [30]

H. Autostereoscopic Displays

A wide range of technologies are used to achieve autostereoscopic displays (both multi-view and 2-view) but unfortunately it is beyond the scope of this article to discuss all of those methods (and crosstalk contributors) in detail here. The most common autostereoscopic screens are based on lenticular and parallax barrier [37] technologies but there are some other technologies in common use.

Autostereoscopic displays also exhibit crosstalk as can be seen in Fig. 19.

With lenticular and parallax barrier autostereoscopic displays, some of the important contributors to crosstalk are:

- the optical quality and type of the lenticular lens / parallax barrier,
- the accuracy of alignment of the lenticular/barrier to the layout of pixels on the display (including the angle of the lenticular lens in slanted lenticular displays),
- the pitch of the individual lenticules / barrier strips relative to the pitch of pixels on the display (which will

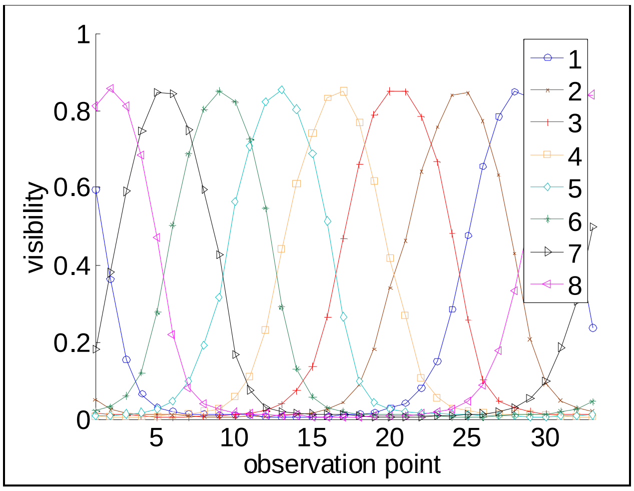

Figure 19. The contribution of each view of an example lenticular multi-view autostereoscopic display to the final viewed image from different observation points. [33]

determine the optimum viewing distance),

- the width of the barrier strips,
- the R,G,B sub-pixel layout of the display,
- the viewing position (in x, y, and z directions), and
- the x-y position on the screen (different areas of the screen may exhibit different levels of crosstalk).

Other types of autostereoscopic displays will have additional and different mechanisms of crosstalk generation than those listed above.

It has been argued that some crosstalk is advantageous to the operation of multi-view autostereoscopic displays [35] – which is different to the way crosstalk is usually considered with other 3D displays.

I. Anaglyph 3D

Anaglyph 3D displays work by coding the left and right views into complimentary colour channels of the display and viewing the display through glasses which have colour filters matched to these colours (e.g. red for the left eye and cyan (blue+green) for the right eye). The process of crosstalk in anaglyph 3D displays is illustrated in Fig. 20.

With anaglyph 3D displays, the important contributors to crosstalk are:

- the spectral quality of the display,
- the spectral quality of the anaglyph glasses (and how well it matches the spectral output of the display), and
- the quality of the anaglyph image generation matrix.

Crosstalk in anaglyph 3D images generally does not vary with screen position or viewing angle, except where the colourimetry of the display changes with viewing angle or screen position. Several papers have analysed crosstalk with anaglyph images in considerable detail [38][39][40].

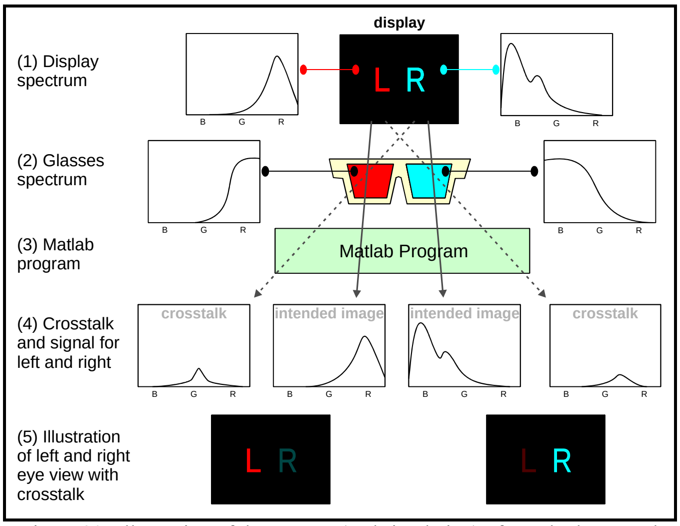

Figure 20. Illustration of the process (and simulation) of anaglyph spectral crosstalk. From the top: (1) Spectral response of display, (2) spectral response of anaglyph glasses, (3) simulation of crosstalk using a computer program, (4) spectral output characteristic of crosstalk and intended image, and (5) visual illustration of left eye and right eye view with crosstalk. [40]

J. Zero Crosstalk 3D Displays

Some 3D displays are inherently free of crosstalk which is usually due to the display having completely separate display channels for the left and right eyes. Examples of zero crosstalk 3D displays include the stereoscope (originally developed by Sir Charles Wheatstone in 1838) and some HMDs (Head Mounted Displays). Zero crosstalk 3D displays have been used to study the perception of crosstalk because they allow the amount of crosstalk to be simulated electronically from 0% to 100% [9].

VI. CROSSTALK REDUCTION

In order to reduce the amount of crosstalk present on a particular stereoscopic display it would be necessary to reduce the effect of one or more of the crosstalk mechanisms of that particular display (as discussed in Section V). Firstly it would be advisable to develop a detailed listing of the crosstalk mechanisms of that display, their relative contribution to overall crosstalk, and an assessment of cost/benefit tradeoffs of any changes. In order to determine the relative contribution of the crosstalk mechanisms to overall crosstalk, it would be necessary to perform a detailed analysis and optical measurement of the display and glasses in many domains (temporal, spatial, and spectral). It would also be beneficial to develop a simulation of crosstalk on that particular display in order to better understand the interrelationship of the individual display properties and how they affect the crosstalk mechanisms, and ultimately their relative contribution to overall crosstalk – see Section VIII.

Once the relative contributions of each crosstalk mechanism are known, it would make some sense to concentrate on the main contributors first to see whether there are any changes that could be made to reduce the effect of these particular crosstalk mechanisms. There will also likely be cost/benefit tradeoffs with any possible changes made to reduce crosstalk. In some cases the 'cost tradeoff' might be increased cost of manufacture of the display or glasses, or the 'cost tradeoff' might be a reduction in some other display performance characteristic. For example, with the conventional Plasma displays tested in [15], the study suggested using shorter persistence phosphors in Plasma displays – but this might result in the increased cost of the display. With time-sequential 3D on LCDs, a reduction in the duty cycle of the shutter glasses might reduce crosstalk, but this might be at the 'cost' of reducing the image brightness [16]. With micro-polarised 3D LCDs, the addition of a black mask will increase the size of the viewing zones (i.e. increasing the size of the zones where low crosstalk is evident), but this might also reduce the brightness of the displays and possibly also increase the cost of manufacture.

Another way to reduce the visibility of crosstalk (ghosting) would be to reduce the contrast ratio of the image or display and/or reduce the brightness of the display (see Section III) – but both of these actions would also reduce the overall quality of the displayed image. Crosstalk cancellation is yet another way of reducing the visibility of crosstalk and is discussed in the next section.

VII. Crosstalk Cancellation

Crosstalk cancellation (also known as anti-crosstalk or ghost-busting) can also be used to reduce the visibility of crosstalk [41][42][43]. While crosstalk cancellation can be effective in hiding the visibility of the crosstalk, the crosstalk is still present but it is hidden by an image processing step before display.

Crosstalk cancellation involves the pre-distortion of the displayed image before display. In simple terms, the amount of leakage that is expected to occur from the unintended view to the intended view is evaluated, and this amount is subtracted from the intended view creating a modified intended view. When the modified intended view is displayed on screen and viewed, the addition of the modified intended view plus the leakage from the unintended view results in the equivalent of the original intended image. Where this simple explanation fails is when the leakage from the unintended view is large (either due to large leakage levels or a bright image in the unintended view) and the intended view is black (or very dark) meaning that the modified intended view would need to go darker than black (negative) in order to cancel out all of the leakage from the unintended view. In this case the black level needs to be raised to accommodate the extra anti-crosstalk that is needed.

Crosstalk cancellation works best when the amount of crosstalk that needs to be cancelled is already relatively small. Large amounts of crosstalk will not be able to be hidden by crosstalk cancellation. It is also important to note that crosstalk cancellation may not work effectively when the amount of crosstalk in a particular 3D display can change significantly due to a change in viewing position or head rotation [7], or when the crosstalk is not pixel-aligned in both views.

VIII. Simulation of Crosstalk

The development of an algorithm to predict crosstalk in a particular stereoscopic display allows a range of what-if scenarios to be explored without going to the expense of doing physical tests or building physical models. For example, how much crosstalk will occur if a particular pixel update method is used, if a particular shutter timing is used, or if a fictitious pair of 3D glasses is used. Hundreds or thousands of what-if scenarios can be simulated at minimal expense perhaps allowing new crosstalk reduction scenarios to be explored.

In order to develop a crosstalk simulation algorithm it is necessary to perform an optical measurement of the display and glasses in many domains (temporal, spatial, and spectral). The accuracy of the crosstalk model will also need to be validated. Crosstalk simulations for parallax barrier 3D [37], anaglyph 3D [40], and time-sequential 3D on CRT [12], PDP [15] and LCD [17] have been developed.

IX. Conclusion

This paper has provided a review of knowledge about stereoscopic display crosstalk with regards to terminology, definitions, mechanisms, measurement, and minimisation. Although it is beyond the scope to this paper to recommend terminology usage to avoid the ambiguities cited in this paper, it is hoped that future work can provide such recommendations. Currently the crosstalk of a particular monitor is not a specification that is regularly released by manufacturers, but it is hoped that in the near future this important determinant of stereoscopic display quality will be readily available to consumers.

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