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REVIEW

Crosstalk in stereoscopic displays: a review

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Abstract. *Crosstalk, also known as ghosting or leakage, is a primary factor in determining the image quality of stereoscopic three dimensional (3D) displays. In a stereoscopic display, a separate perspective view is presented to each of the observer's two eyes in order to experience a 3D image with depth sensation. When crosstalk is present in a stereoscopic display, each eye will see a combination of the image intended for that eye, and some of the image intended for the other eye—making the image look doubled or ghosted. High levels of crosstalk can make stereoscopic images hard to fuse and lack fidelity, so it is important to achieve low levels of crosstalk in the development of high-quality stereoscopic displays. Descriptive and mathematical definitions of these terms are formalized and summarized. The mechanisms by which crosstalk occurs in different stereoscopic display technologies are also reviewed, including micropol 3D liquid crystal displays (LCDs), autostereoscopic (lenticular and parallax barrier), polarized projection, anaglyph, and time-sequential 3D on LCDs, plasma display panels and cathode ray tubes. Crosstalk reduction and crosstalk cancellation are also discussed along with methods of measuring and simulating crosstalk. © 2012 SPIE and IS&T.* [DOI: 10.1117/1.JEI.21.4.040902]

1 Introduction

Stereoscopic three dimensional (3D) displays present a 3D image to an observer by sending a slightly different perspective view to each of an observer's two eyes. The visual system of most observers is able to process the two perspective images so as to interpret an image containing a perception of depth by invoking binocular stereopsis so they can see it in 3D.

There are a wide range of technologies available to present stereoscopic 3D images to an audience, and the discussion in this paper will be limited to so-called "plano-stereoscopic" displays[1]—i.e., displays that present both left and right perspective images on the same planar surface and then use a coding/decoding scheme (e.g., glasses) to present the correct image to each eye. Examples of such plano-stereoscopic displays include liquid crystal display (LCD) or plasma display panel (PDP) 3D TVs viewed using active shutter 3D glasses, 3D LCD monitors or 3D cinema systems viewed using passive polarized 3D glasses, or autostereoscopic displays utilizing either a parallax barrier or lenticular lens sheet to allow the 3D image to be viewed without 3D glasses. The aim of all of these displays is to send separate left- and right-eye views to each eye, but due to various inaccuracies, which will be described in detail later in the paper, the image intended only for one eye may be leaked to the other eye. This leakage of one image channel to the other in a stereoscopic display system is known as crosstalk or sometimes ghosting or leakage. Crosstalk is a primary factor affecting the image quality of stereoscopic 3D displays and is the focus of this review paper.

This paper starts by providing a summary of descriptive and mathematical definitions of crosstalk and related terms as they are now in common usage, along with a short summary of the perceptual effects of crosstalk. The bulk of the paper describes the various methods by which crosstalk can occur in various stereoscopic display technologies. This is followed by a description of the methods of measuring crosstalk, a discussion of ways in which crosstalk can be reduced, and last, some coverage of the role of simulation of crosstalk analysis.

2 Terminology and Definitions

In electronic engineering, the term "crosstalk" has been used as far back as the 1880s[2] to describe the leakage of signals between parallel laid telephone cables. Crosstalk in stereoscopic displays has been a recognized term at least since the 1930s,[3] if not earlier.

The use of the term "crosstalk" in the stereoscopic literature is very common—present in over 15% of all documents in a major stereoscopic literature collection.[4,5] The term is also often written as "cross talk,"[6] "cross-talk,"[7] or "X-talk,"[6] but "crosstalk" (without an intermediate space or hyphen) is the most commonly used variant, so that is the form that will be used in this paper.[4] Other variants with the same meaning include "interocular crosstalk,"[8,9] "crosstalk ratio,"[10] and "3D crosstalk."[11]

Despite the term's long history of usage in the stereoscopic technical literature, many papers in the past have simply used the term without providing a descriptive or mathematical definition, nor citing a reference to such. The terms crosstalk and ghosting have been used interchangeably in some of the published literature, whereas modern usage provides separate definitions for these terms—this will be explained in the following sections. Unfortunately there are also some contradictory uses of the terminology in the literature.

The technical field of stereoscopic displays has grown considerably even in just the past five years and in order to foster the continued development of the field, it is important to have a common knowledge of the terminology and definitions of crosstalk and related terms. The following subsections provide a summary of definitions of the important terms in this field and identify ambiguities that still remain

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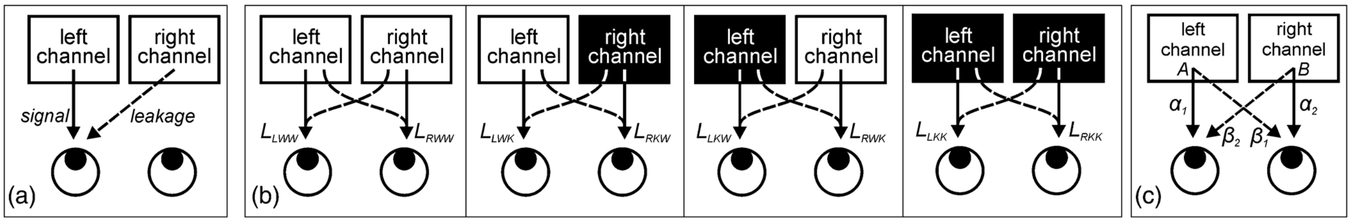

Fig. 1 An illustration of the terms and luminance measurement variables used in this paper with respect to the left and right image channels and left and right eyes. The left and right image channels are shown separated here for illustrative purposes but would be visually overlaid on a stereoscopic display. (a) Illustration of the terms signal and leakage. (b) Illustration of the eight luminance variable L variants. The first subscript is the eye position (**L**eft or **R**ight) that the luminance is measured from. The second subscript is the value (blac**K** or **W**hite) of the desired image channel, and the third subscript is the value (blac**K** or **W**hite) of the undesired image channel. For example, LRWW specifies the luminance measured at the right eye position when the right image (desired) channel is set to white and the left image (undesired) channel is also set to white, which corresponds to the summation of light from the right channel plus a (hopefully) small amount of light from the left channel. (c) Illustration of the transfer function variables used in Huang's definition of "system crosstalk" (see Sec. 2.2.3).[16]

and could otherwise cause confusion for those reading the published literature.

Stereoscopic terminology can be used to describe a principle in general terms and can also be used to quantify a physical property—this paper will review both the descriptive and mathematical definitions where applicable.

2.1 *Descriptive Definitions*

A selection of descriptive definitions of crosstalk from the literature (1987 to 2009) were previously examined.[4] It was found that despite some variations in wording, there was a common theme—i.e., light from one image channel leaking into another. The following descriptive definition will be used in this paper (based on Lipton[12]):

Crosstalk: the incomplete isolation of the left and right image channels so that the content from one channel is partly present in another channel.

There is also a mathematical definition of crosstalk, which will be provided in the following section. In the general stereoscopic literature and the lay media, the terms "crosstalk" and "ghosting" have often been used interchangeably,[4] but in scientific discussion it is worthwhile to differentiate these terms. Crosstalk and ghosting appear to have been first documented as separate terms in 1987 by Lipton,[13] which leads us to the following definition:

Ghosting: the perception of crosstalk.

The term "leakage" is also commonly used in discussions about crosstalk, however, a formal definition was not found in the stereoscopic literature.[4] The following definition was developed based on dictionary definitions and current usage in the field:[4]

Leakage: the (amount of) light that leaks from one stereoscopic image channel to another.

Leakage is also known as "crosstalk luminance" and "unintended luminance."[14]

2.2 *Mathematical Definitions*

Crosstalk can be used as a metric to express how much crosstalk occurs in a particular stereoscopic display system. There are several mathematical definitions of crosstalk in common usage as explained below.

2.2.1 *Crosstalk definition 1*

In its simplest form crosstalk can be mathematically defined[15] as:

$$\text{Crosstalk}(\%) = \frac{\text{leakage}}{\text{signal}} \times 100, \tag{1}$$

where "leakage" is the luminance of light that leaks from the unintended channel to the intended channel, and "signal" is the luminance of the intended channel, as illustrated in Fig. 1(a).

In common practice, two luminance measurements are usually taken (from the intended eye position) with: (a) full-black in the intended channel and full-white in the unintended channel (this corresponds with "leakage" above) and (b) full-white in the intended channel and full-black in the unintended channel (this corresponds with "signal" above).

This can also be expressed as:

$$C_L = \frac{L_{\text{LKW}}}{L_{\text{LWK}}} \tag{2}$$

and

$$C_R = \frac{L_{\text{RKW}}}{L_{\text{RWK}}}, \tag{3}$$

where C_L and C_R are crosstalk for the left and right eyes (which can be presented as a number or a percentage), and L_{LKW}, L_{LWK}, L_{RWK}, L_{RWK} are the luminance measured from the **L**eft or **R**ight eye position (first subscript) with **W**hite or blac**K** in the desired image channel (second subscript) and **W**hite or blac**K** in the undesired image channel (third subscript) as illustrated in Fig. 1(b).[*,†,‡] The shortcoming of this definition is that it does not consider the effect of a non-zero

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[*] It is worth noting that some publications use variable C to denote crosstalk, whereas other publications use variable C for contrast[17] and variable X or χ for crosstalk.[14,18]

[†] Some papers define the subscripts for the luminance measurement variables differently than we have used in this paper. Specifically, sometimes the second luminance (L) subscript is the setting (**W**hite or blac**K**) of the "left channel" (as opposed to the "desired channel"), and the third subscript is the setting (**W**hite or blac**K**) of the "right channel" (as opposed to the "undesired channel"). This makes no difference for the left-eye luminance variables, but results in a transposition of the second and third subscript meanings for the right-eye luminance variables. The "desired, undesired" definition is the more common, and is more extensible for crosstalk in multi-view displays, so this is what has been used in this paper.

[‡] When testing PDPs, test images should only fill a small portion of the screen in order to avoid triggering the automatic brightness limiter (ABL) (which reduces the intensity of high-brightness scenes to reduce peak power consumption) which would otherwise bias measurement results.[19]

black level of the display. Some displays are incapable of outputting zero luminance for full-black (e.g., LCDs)—this non-zero black level does not contribute to visible crosstalk (ghosting) and hence would bias the crosstalk calculation using this first definition. If the display black level is set at zero luminance, definition 1 is entirely valid, but definition 1 should only be used with displays which can have zero black level, and are set up that way.

2.2.2 *Crosstalk definition 2*

The second mathematical definition removes the effect of non-zero black level by subtracting the black level luminance:

$$\text{Crosstalk}(\%) = \frac{\text{leakage} - \text{black level}}{\text{signal} - \text{black level}} \times 100. \tag{4}$$

Several papers support this second formulation (but with different variable names).[4,10,14,17,20]

This equation can also be expressed as:

$$C_L = \frac{L_{\text{LKW}} - L_{LKK}}{L_{\text{LWK}} - L_{\text{LKK}}} \tag{5}$$

and

$$C_R = \frac{L_{\text{RKW}} - L_{\text{RKK}}}{L_{\text{RWK}} - L_{\text{RKK}}}, \tag{6}$$

where the variables are as defined in Sec. 2.2.1 and L_{LKK} and L_{RKK} are the black level of the display.[†‡]

Both of these definitions use what is commonly referred to as a black-white crosstalk test because full-black and full-white test signals are used.[21‡] Full-white and full-black signals are used because maximum ghosting usually occurs when the pixels in the desired-eye channel are full-black and the same pixels in the opposite eye-channel are full-white.

The differences between these two mathematical definitions of crosstalk (definitions 1 and 2) create an ambiguity—therefore when quoting crosstalk values it is important to specify which definition is being used, and similarly if reading a report or technical paper, it is important to determine which definition has been used to calculate the results quoted.

2.2.3 *System crosstalk and viewer crosstalk*

In 2000, Huang et al.,[16] defined two new terms in an attempt to disambiguate the terminology relating to crosstalk:

System crosstalk: the degree of the unexpected leaking image from the other eye.

Viewer crosstalk: the crosstalk perceived by the viewer.[22]

As defined, system crosstalk is independent of the image content (determined only by the display), whereas viewer crosstalk varies depending upon the content. These definitions are similar to the definitions of crosstalk and ghosting provided in Sec. 2.1 (based on Lipton[12])—but are not exactly the same. The definition of viewer crosstalk includes the effect of image contrast (and indirectly the effect of parallax) but Lipton's definition of ghosting includes any perception effect.

These are defined mathematically as:[16]

$$\text{System crosstalk (left eye)} = \beta_2/\alpha_1, \tag{7}$$

$$\text{Viewer crosstalk (left eye)} = B\,\beta_2/A\,\alpha_1, \tag{8}$$

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"[16] and vice versa for the other eye. 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 on the screen) in the right-eye image, as illustrated in Fig. 1(c). It is worth noting that Eq. (7) does not include the effect of black level—as is also the case with crosstalk definition 1 in Sec. 2.2.1.

The philosophy upon which system crosstalk is defined is quite different to crosstalk definitions 1 and 2 provided earlier. Variables α_1 and β_2 are essentially transfer functions which characterize the optical performance of the entire *system* (from image display, through the glasses or image separation stage, to viewed luminance) and hence is probably the reason that the authors called it system crosstalk. In comparison, definitions 1 and 2 are observer-centric or output-luminance centric—based only on measurements of luminance at the viewer location. In order to calculate the system performance variables α_1 and β_2, both the source and output luminance need to be measured, but with some displays the source luminance cannot be directly measured (e.g., lenticular or parallax barrier displays). Fortunately, if some assumptions are made, the equation can be converted to an equation based on properties that can be easily measured, and hence can be expressed similarly to Eq. (1).

In 2009, Huang et al.[22] provided a revised definition of system crosstalk that includes the effect of black level.[§]

$$\text{SCT}_L = \frac{L_{\text{LKW}} - L_{\text{LKK}}}{L_{\text{LWK}} - L_{\text{LKK}}} \tag{9}$$

and

$$\text{SCT}_R = \frac{L_{\text{RKW}} - L_{\text{RKK}}}{L_{\text{RWK}} - L_{\text{RKK}}}, \tag{10}$$

where SCT_L and SCT_R are the system crosstalk for the left and right eyes, and L_{LKW}, etc. are defined per Sec. 2.2.1.[†]

As a result of this change of definition, it is important to establish which definition of system crosstalk (2000[16] or 2009[22]) is being used when it appears in a publication. Equations (9) and (10) are equivalent to crosstalk definition 2 provided above [Eqs. (5) and (6)].

2.2.4 *Gray-to-gray crosstalk*

In most stereoscopic displays crosstalk is an additive process and roughly linear, so using the black-white test to measure crosstalk and expressing the result as a simple percentage is representative of the display's overall crosstalk, but this is not true for all stereoscopic displays, particularly 3D LCDs or 3D PDPs using shutter glasses, and hence a more detailed definition is needed. For displays in which the crosstalk process is highly nonlinear, the gray-to-gray crosstalk measurement should be used.

In 2010, three papers[21,23,24] all separately defined a new term: "gray-to-gray crosstalk."

[§] These equations have been reworked (from that published by the original authors) to a scheme which matches the notation used throughout in this paper.

Shestak et al.,[21] provided the following definition.[§]

$$C_{Lij} = \frac{L_{Lij} - L_{Lii}}{L_{Ljj} - L_{Lii}} \tag{11}$$

and

$$C_{Rij} = \frac{L_{Rij} - L_{Rii}}{L_{Rjj} - L_{Rii}}, \tag{12}$$

where C_{Lij} is crosstalk for the **L**eft eye (first subscript) calculated for the matrix of the desired image channel (second subscript) and the undesired image channel (third subscript) gray level combinations i and j,[†] L_{Lij} is the luminance measured from the **L**eft eye position (first subscript) with i gray level in the desired image channel (second subscript) and i gray level in the undesired image channel (third subscript), and so on.

Jung,[23] Pan,[24] ICDM,[14] and Chen[25] have also provided definitions for gray-to-gray crosstalk which vary from that of Shestak,[21] so again, it is important to know which definition is used when gray-to-gray crosstalk values are published. Apart from variable notation differences, the main difference between definitions of gray-to-gray crosstalk is the choice of variables on the denominator and the use of absolute values. It would be useful to see a comparison between these definitions to know the pros and cons of each and help decide on the most useful definition—like Järvenpää et al., have done for autostereoscopic crosstalk definitions.[26]

There are some difficulties of these gray-to-gray crosstalk definitions—first, a singularity is present when $i = j$ with some definitions, and secondly, the crosstalk values are not perceptually relevant. Teunissen et al.,[27] and Shestak et al.,[28] have described an extension of this work to provide a perceptually relevant measure of the visibility of crosstalk (ghosting) in relation to the gray-to-gray crosstalk measurement.

2.2.5 *Multi-view autostereoscopic (inter-view) crosstalk*

The crosstalk definitions described so far only apply to two-view stereoscopic displays, but the definition can be extended to apply to multiview autostereoscopic displays, where it can also be called inter-view, adjacent-view or inter-zone crosstalk.

Järvenpää et al.[18,29] have provided the following definition of crosstalk for multi-view autostereoscopic displays.[§]

$$C_i(\theta) = \frac{\sum_{j=1}^{\#\text{ of views}}[L_j(\theta) - L_K(\theta)] - [L_i(\theta) - L_K(\theta)]}{L_i(\theta) - L_K(\theta)}, \tag{13}$$

where $C_i(\theta)$ is the calculated crosstalk curve for each view i as a function of the horizontal viewing angle θ, $L_j(\theta)$ is the measured luminance curve for view j when that view is white and the other views are black, $L_i(\theta)$ is the measured luminance curve for view i (the view for which the crosstalk is being determined) when that view is white and the other views are black, and $L_K(\theta)$ is the measured luminance curve when all display pixels (all views) are black.

Crosstalk can also vary with pixel position on the screen and vertical viewing angle of the observer, and the crosstalk equation can be extended to include these variables if needed.[18]

The above definition applies only to autostereoscopic displays with discrete views—a different formula would be needed for autostereoscopic displays with continuous views.[18]

2.2.6 *Extinction and 3D contrast*

Two other related terms are:

Extinction and **extinction ratio**: "The ratio of the luminance of the correct eye [view] to the luminance of the unwanted 'ghost' from the image intended for the opposite eye"[9]—usually expressed as a ratio, for example '50:1.'

3D contrast: Unfortunately multiple definitions exist. Boher[17] and ISO[18] define 3D contrast as the inverse of (black-white) 3D crosstalk (definition 2 above). ISO[18] also defines 3D contrast for multi-view autostereoscopic displays as the inverse of multi-view autostereoscopic crosstalk [Eq. (13) above]. However, ICDM[14] defines 3D contrast as the arithmetic mean of the two (left and right) monocular contrasts, where monocular contrast is defined as the luminance ratio of both channels' white level to both channels' black level. ICDM[14] defines system contrast as $L_{\mathrm{LWK}}/L_{\mathrm{LKW}}$ (the inverse of crosstalk definition 1 above).

3 Perception of Crosstalk

The perception of crosstalk in stereoscopic displays has been studied widely.[10,22,30–34] It is broadly acknowledged that the presence of high levels of crosstalk in a stereoscopic display is detrimental. Wilcox and Stewart[35] reported that crosstalk was the most important attribute in determining image quality for 75% of their observers. The effects of crosstalk in a stereoscopic image include ghosting and loss of contrast, loss of 3D effect and depth resolution, viewer discomfort,[36] reduced limits of fusion, reduced image quality and reduced visual comfort,[9] and reduced perceived magnitude of depth.[37]

The perception of crosstalk (ghosting) increases with increasing image contrast and increasing binocular parallax of the image.[21,30,33] This principle is illustrated in Fig. 2 which summarizes an experiment performed by Pastoor.[30] One example of this principle is that a stereoscopic image with high contrast (lots of bright whites against a deep black background—e.g., a star field image) will exhibit more ghosting on a particular stereoscopic display than will an image with low contrast. Other image content aspects that can also affect perception of crosstalk include focus and motion blur (blur can disguise crosstalk)[38] and the extent of objects (crosstalk is more visible on thin objects).[39]

The stereoscopic literature provides various advice on the amounts of crosstalk that are acceptable and unacceptable. Some examples include:

- "Difference [change] in crosstalk between [from] 2% and [to] 6% significantly affected image quality and visual comfort" (Ref. 40 paraphrasing Ref. 9)
- "In order to reproduce a reasonable depth range (up to 40 minarc) on a high-contrast display (100:1), crosstalk should be as low as 0.3%"[30]

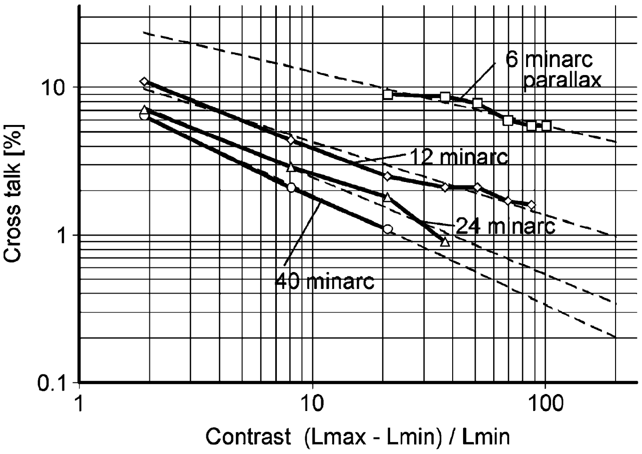

Fig. 2 Visibility thresholds for crosstalk as a function of local image contrast and binocular parallax as conducted by Pastoor.[30] The graph shows that "visibility of crosstalk increases (i.e., the threshold value is lowered) with increasing contrast and increasing binocular parallax (depth) of the stereoscopic image."[30] The four line segments on the graph show the threshold of visibility of crosstalk for four different values of stereoscopic image parallax (6, 12, 24, and 40 min of arc) and a selection of different image contrast levels (ranging from 2:1 to 100:1). With the same image contrast (e.g., 20:1), it can be seen that the threshold of visibility of crosstalk decreases for increasing levels of parallax, meaning that ghosting is more visible with higher levels of stereoscopic image parallax. Keeping parallax constant (e.g., following the 12 minarc line), it can be seen that the threshold of visibility of crosstalk decreases with increasing image contrast, meaning that crosstalk is more visible with higher levels of image contrast. Image: © ITE and SID.[30]

- "Crosstalk . . . visibility threshold of about 1% to 2%" (Ref. 40 paraphrasing Ref. 31)
- "Crosstalk level of about 5% is sufficient to induce visual discomfort in half of the population"[32]
- "Results show that a 1% increment in crosstalk is visible, while 5.8% crosstalk is perceptible, but not annoying"[40]
- "For optimal image quality, crosstalk levels should be held below 1%. However, most of the depth percept is maintained at crosstalk levels of up to 4%"[37]
- "A significant decrease in perceived depth was observed with as little as 2–4% crosstalk"[41]

As can be seen above, unfortunately there is considerable variability between the results and guidelines of different papers. This might just be a reflection of the nature of perception-based studies, but results can also be influenced by differences between stereoscopic display technologies, measurement methods, experimental conditions, and display content. There may also be different acceptability thresholds for different usage types—entertainment viewing may be more tolerant of crosstalk than an industrial fine tele-operation task. It is also important to understand that most of the current measures of crosstalk are not perceptually relevant—hence more research is needed in this area.[27,28]

The reason for determining the threshold of visibility of crosstalk is that it can be very difficult to totally eliminate crosstalk in a particular stereoscopic display technology, whereas if the level of crosstalk can be reduced to a point at which it is not noticeable to the observer, this may allow a more technically and economically viable solution. There is still a great deal to be learnt about the perception of crosstalk and there is considerable scope for more research in this area.[27,28]

4 Crosstalk Mechanisms

Figure 3 shows the flow of images from the capture of the perspective images with a camera, through to the display of the images on a stereoscopic display, and subsequently viewing and perception by an observer. Crosstalk can occur in the capture, storage/transmission, display and separation stages—this paper focuses most of its attention on how crosstalk occurs in the display and separation stages.

One of the fascinating things about crosstalk is that the mechanisms by which it occurs can vary considerably from one stereoscopic display technology to another.

The sections below summarize 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, so it is not possible to discuss all possible stereoscopic display technologies in one short paper. This paper provides the reader with information about the factors which cause crosstalk in a selection of the most common stereoscopic displays and hopefully provide clues as to the crosstalk mechanisms in other displays not specifically discussed.

4.1 *Time-Sequential 3D Using Active Shutter Glasses*

The time-sequential 3D display method is a widely used technique to display stereoscopic images to an observer.[‖] It relies on the alternate presentation of left and right images on the display surface combined with a pair of active shutter 3D glasses to gate the appropriate image to each eye.[¶] In the past, mechanical shutters[42] and lead-lanthanum-zirconate-titanate (PLZT) shutters[43,44] have been used in the glasses, but current shutter glasses almost exclusively use a liquid crystal (LC) cell in front of each eye to sequentially occlude the images.[45] The optical transmission properties of the liquid crystal shutter are a key determinant in the amount of crosstalk present with the time-sequential 3D displays which use shutter glasses.

The optical transmission performance of an example pair of shutter glasses is shown in Fig. 4. In this figure it can be seen that:

- the LC shutters have non-zero transmission in the opaque state, which means that some light still leaks through when the shutter is nominally in the blocking condition,
- the rise-time and fall-time are not instantaneous—sometimes taking several milliseconds to change from one state to another, and
- the performance at different optical wavelengths is not all the same.

[‖] The time-sequential stereoscopic 3D method is also known as time-multiplexed, field-sequential, frame-sequential, alternate frame, or active-stereo.

[¶] 3D shutter glasses are also known as active shutter glasses, liquid crystal shutter (LCS) glasses, and sometimes incorrectly as LCD shutter glasses. The LC cells in 3D shutter glasses are not displays (just shutters), so the term "LCD shutter glasses" is incorrect.

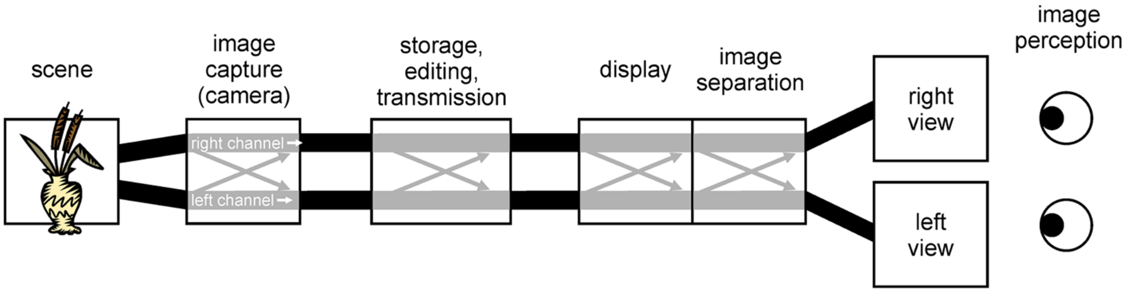

Fig. 3 A flow diagram showing the transfer of stereoscopic images from image capture through to image viewing and perception by the observer. Crosstalk between the left and right image channels can occur in the capture (camera) stage, storage/editing/transmission stage, image display (light generation), and image separation (3D glasses or autostereoscopic optical layer) stages. Most crosstalk usually occurs in the display and image separation stages.

In addition to the attributes listed above, the optical performance of the LC cell also varies with viewing angle through the cell. The best performance is usually achieved when the visual angle is perpendicular to the cell and drops off as the viewing angle varies from perpendicular.

There can also be considerable variability in the optical performance of the LC shutter between various makes of shutter glasses. Figure 5 provides an example of the performance of eight different pairs of shutter glasses and highlights the large differences possible. These optical differences can also affect crosstalk performance.

Next it is necessary to consider how the shutters operate in coordination with the sequence of the displayed left and right images. Figure 6 provides an illustration of how a pair of shutter glasses interacts with the image output sequence of a theoretical time-sequential stereoscopic display. Figure 6(a) provides an illustration of the light output of the left-right image sequence, with around 1 millisecond of blanking time between images. Figure 6(b) shows the transmission response of the left-hand LC shutter (the green response from Fig. 4). Figure 6(c) is an illustration of the image intensity that the left-eye will see when viewing the display through the shutter glasses. The intensity of the desired image (signal) is indicated in green and it can be seen that the intensity of the beginning of the left image is reduced because of the long rise-time of the shutter. The intensity of the undesired image (leakage) is indicated in red—in this case this represents the intensity of the right image as seen by the left eye caused by the shutter not fully switching to 0% transmission in the opaque state. The amount of crosstalk illustrated in Fig. 6(c) is approximately 7% (calculated by dividing the red area by the green area—assuming a zero black level display).

Another aspect to consider in reference to Fig. 6 is that if the shutters switch too early or too late relative to the sequence of displayed images, the incorrect image will be gated to each eye, hence causing crosstalk.

Another item to note in the example of Fig. 6 is that the transition of the left LC shutter from open to closed occurs within the blanking interval between the display of the left and right images. The presence of a blanking interval is useful in helping to hide the transition of the LC shutters. Some displays don't have a blanking interval, which can compromise crosstalk performance.

Very few stereoscopic displays are able to achieve the theoretical time-sequential display output illustrated in Fig. 6(a)—Digital light projection (DLP) or organic light emitting diode (OLED) displays come close to this performance, but there will typically be three deviations from this ideal performance:

- **Image persistence.** In cathode ray tube (CRT) and PDP displays, the phosphors which emit light have an exponential decay in light output from when they are first energized, meaning that the image on the

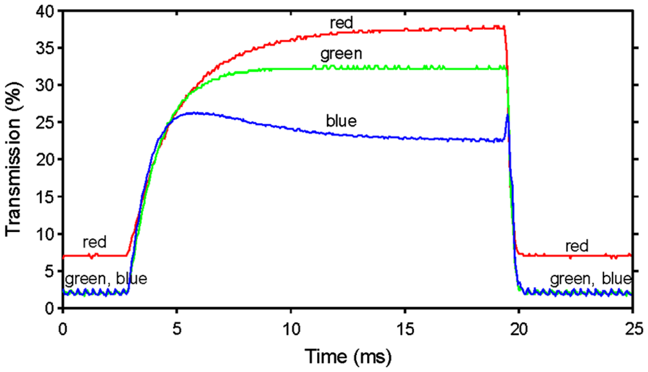

Fig. 4 The transmission versus time response of an example pair of active shutter glasses at red, green and blue wavelengths (measured using red, green and blue light emitting diode (LED) continuous light sources).[46]

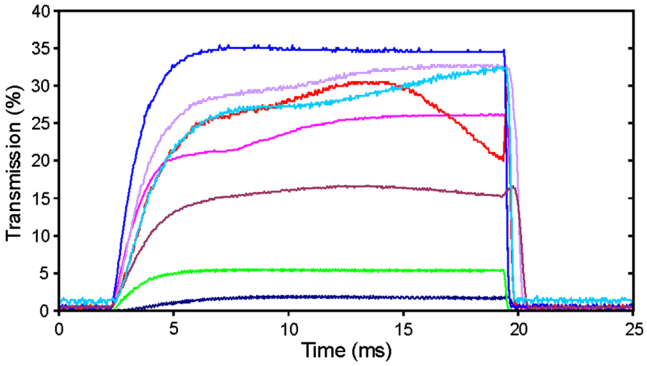

Fig. 5 The transmission versus time response of a selection of different LCS glasses at green wavelengths (measured using a green LED continuous light source). There can be a wide variability of performance between different shutter glasses.[46]

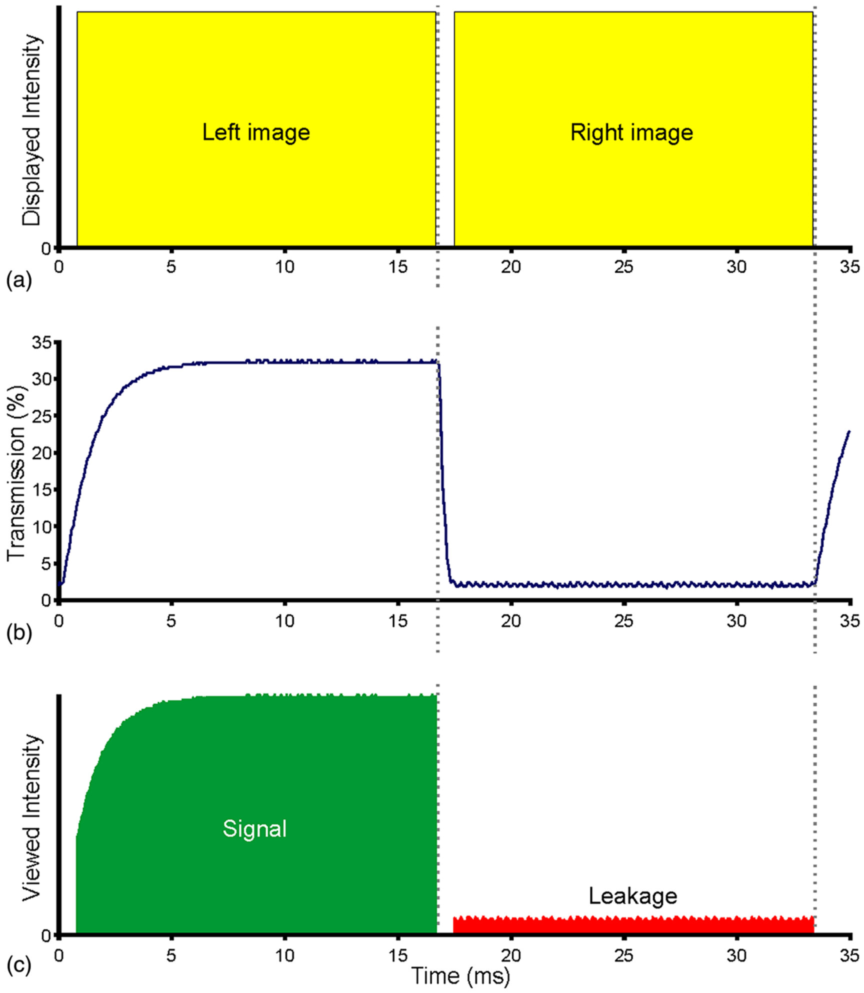

Fig. 6 An illustration of how a pair of shutter glasses interacts with the left/right image sequence of a theoretical time-sequential stereoscopic display. (a) The sequence of left and right images output by a theoretical display with instantaneous pixel response. (b) The transmission versus time of the left-eye LC shutter. (c) The image intensity as viewed through the left-eye of the LC glasses.

display persists for a nominal period of time.[46,47] Displays which exhibit long image persistence will typically exhibit more crosstalk because light from one frame is still being output during the period of the following frame.

- **Pixel response rate.** In LCDs it takes a measurable period of time for a pixel to change from one gray level to another and this is referred to as the pixel response rate.[48] A display with a slow pixel response rate will typically exhibit more crosstalk than a display with a fast pixel response rate.
- **Image update method.** This term describes the way in which the screen is updated from one image to another. In some displays, new images are scanned or addressed from the top to bottom (e.g., CRTs[46] and LCDs[48]), whereas some displays update all pixels on the screen at the same time (e.g., DLPs[49] and PDPs[47]). In simple terms, it will be easier to synchronize a shutter to a display whose pixels all update at the same moment. When shutter glasses are used with a scanned display, the amount of crosstalk present will usually vary with screen position due to the different phase of the switching of the shutter relative to the time the pixels change at different screen coordinates.

These display performance attributes will affect crosstalk performance by varying amounts as will be discussed in more detail in Secs. 4.1.1 through 4.1.4 in relation to specific display technologies.

In summary, the methods by which crosstalk can occur in systems using shutter glasses are:

- The optical performance of the liquid crystal cells—the amount of transmission in the opaque state, the rise-time, the fall-time, and the amount of transmission in the clear state.
- The relative timing (synchronization) of the glasses with respect to the displayed images.
- The angle of view through the liquid crystal cells—the optical performance of the cells usually falls off with viewing angles which are off perpendicular.
- The temporal performance of the particular display being used and how this interacts with the temporal performance of the shutters.

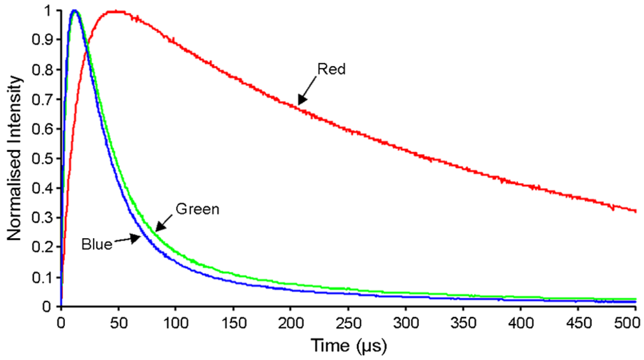

Fig. 7 Phosphor intensity versus time response for the three phosphors of a typical cathode ray tube (CRT) display.[46]

The display-particular aspects will now be discussed in Secs. 4.1.1 through 4.1.4.

4.1.1 *Time-sequential 3D on CRTs*

CRT displays were the first display technology to be used with liquid crystal shutter glasses when they were introduced in the 1980s so that is where we will start our discussion. CRTs generate an image by scanning an electron beam over a phosphor-coated surface on the inside the screen. As the electron beam is scanned across the display surface from top to bottom, the phosphors emit light as they are hit by the electron beam and exponentially decay over time, as illustrated in Fig. 7. In this figure it can be seen that the red phosphor has a longer decay (persistence) than the green and blue phosphors. CRT displays are considered to be an impulse-type display because the displayed image is generated by a series of pulses of light.[50]

The interaction of shutter glasses with the light output of a CRT is illustrated in Fig. 8. As the electron beam energizes the phosphor it outputs a peak of light which then decays exponentially (exaggerated here for illustrative purposes). This figure considers the leakage from the left-image channel into the right-eye view, so the phosphor is shown energized during the left-eye period when the right-eye shutter is closed. When the right-eye shutter opens during the second vertical blanking interval (VBI2), the phosphor is still outputting some light from the previous image period—particularly for pixel positions at the bottom of the screen, which are energized shortly before VBI2. The bottom of Fig. 8 illustrates the amount of light leakage from the left image channel into the right-eye view—the area under the solid red curve from end of the first vertical blacking interval (VBI1) to the start of VBI2 represents leakage due to the incomplete extinction of the shutter, and the area under the solid red curve from start of VBI2 onwards represents leakage due to long phosphor persistence.

Figure 9 illustrates the spatial variation of crosstalk on a time-sequential CRT display. CRTs will exhibit more crosstalk at the bottom of the screen because phosphors at the bottom of the screen will be energized soon before the shutter is opened for the other eye and therefore more of that phosphor's decay tail will be visible to the other eye.

With time-sequential 3D on a CRT, the important factors which cause crosstalk[13,46,51] are therefore:

- the performance of the liquid crystal cells in the shutter glasses (see Sec. 4.1),
- the amount of phosphor persistence—the time that it takes for the phosphors to stop glowing after they have been energized (see Fig. 7) (Long phosphor persistence will cause more crosstalk because the light

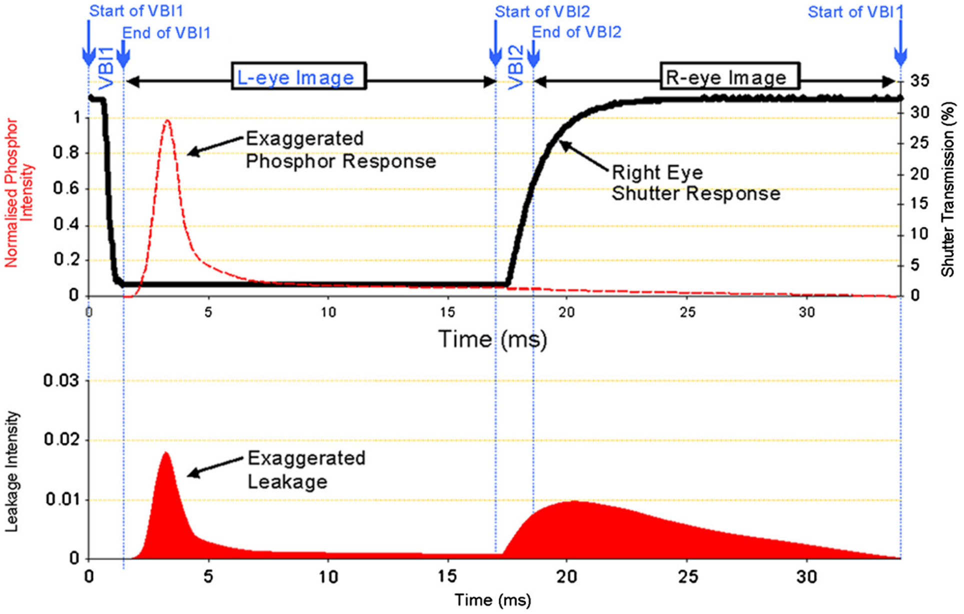

Fig. 8 Illustration of crosstalk on a cathode ray tube (CRT) (with exaggerated phosphor response for illustrative purposes).[46] Top: phosphor response and shutter response. The phosphor is energized during the first frame (L-eye) period, when the shutter is closed, and exponentially decays. Bottom: multiplication of phosphor response by the shutter response to give the amount of leakage. The area under the solid red curve from end of VBI1 (vertical blanking interval) to the start of VBI2 represents crosstalk due to the incomplete extinction of the shutter, and the area under the solid red curve from start of VBI2 onwards represents crosstalk due to long phosphor persistence.

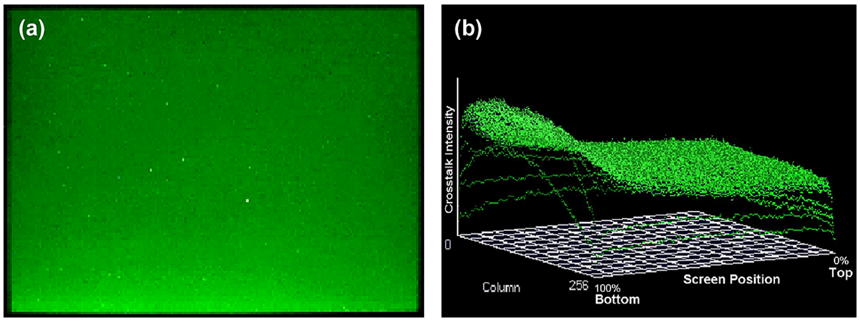

Fig. 9 Illustration of spatial variation of crosstalk on a cathode ray tube (CRT), with increased crosstalk at the bottom of the screen: (a) actual screen photograph of CRT crosstalk through a pair of active shutter glasses, and (b) histogram of measured CRT crosstalk.[46]

from the first frame is still being output during the period of the following frame),

- the timing of the shuttering of the glasses with respect to the display of images on the screen—it is important that the switching of the shutters occurs during the vertical blanking interval (VBI) to minimize crosstalk (see Fig. 8), and
- the x-y coordinates on the screen—the bottom of the screen will exhibit more crosstalk than the top of the screen due to the way that the electron beam scans the display from top to bottom (see Fig. 9).

4.1.2 *Time-sequential 3D on PDPs*

PDPs with time-sequential 3D display capability were first experimentally demonstrated in 1998[52,53] and first commercially released in 2008 by Samsung.[54] PDPs generate light using phosphors which are energized up to 10 times per frame (see Fig. 10). These 10 pulses (subframes) per frame have different durations (sustain time) and hence luminance, in a binary sequence from longest duration to shortest duration. Different gray levels are achieved for each pixel by firing or not firing the phosphors for each pixel in none, some, or all of the 10 subframes per frame. This is quite different from the way that gray-levels are produced on a CRT which has analog control over the intensity of the pulse of light from the phosphors, whereas with a PDP each individual pulse of light per pixel per subframe can only be on or off—there is no in-between. Therefore, ten individual pulses of pre-determined intensity are fired selectively to collectively produce different gray levels.[47]

With further reference to Fig. 10, it can be seen that the phosphors in PDPs also (like CRTs) exhibit an exponential decay in light output after they have been energized—this is particularly visible in the period between 16 ms and 33 ms with the red and green color channels. Figure 11 illustrates the interaction of shutter glasses with the light output of another conventional PDP display (different than Fig. 10). In Fig. 11(a) it can be seen that the long phosphor persistence from 17 ms onwards causes there to be light output from the previous frame when the right shutter opens which will in turn cause crosstalk. Figure 11(b) illustrates the relative intensity of the signal (left image channel into the left-eye view) and leakage (left image channel into the right-eye view) components. Additionally, the area under the red leakage curve from 0 to 17 ms represents leakage due to the incomplete extinction of the shutter, and the area under the red leakage curve from 17 ms onwards represents leakage due to long phosphor persistence.

With time-sequential 3D on a PDP, the important contributors to crosstalk[47] are therefore:

- the performance of the liquid crystal cells in the shutter glasses (see Sec. 4.1),
- the amount of phosphor persistence—the time that it takes for the phosphors to stop glowing after they have been energized (see Fig. 10),
- the timing of the shuttering of the glasses relative to the display of images on the screen (see Fig. 11), and
- the particular gray level value of a displayed pixel and therefore which subframes are fired—a subframe fired immediately before the transition point will dump more light into the following frame due to phosphor persistence than for a subframe which is fired earlier whose phosphor persistence will have had more time to decay before the next frame (see Fig. 11).

Crosstalk does not vary with screen position on PDPs except where the visual angle through the shutter glasses might be non-perpendicular for viewing the corners of the screen.

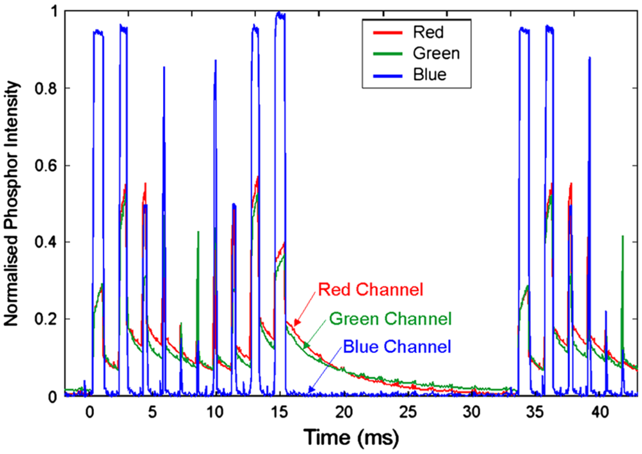

Fig. 10 The time-domain light output of an example plasma display (showing alternating frames of 100% white and black). The vertical axis is the normalized phosphor intensity.[47] This graph illustrates the 10 pulses per frame used to construct images with various gray levels and the long phosphor persistence of the red and green channels (of this particular display).

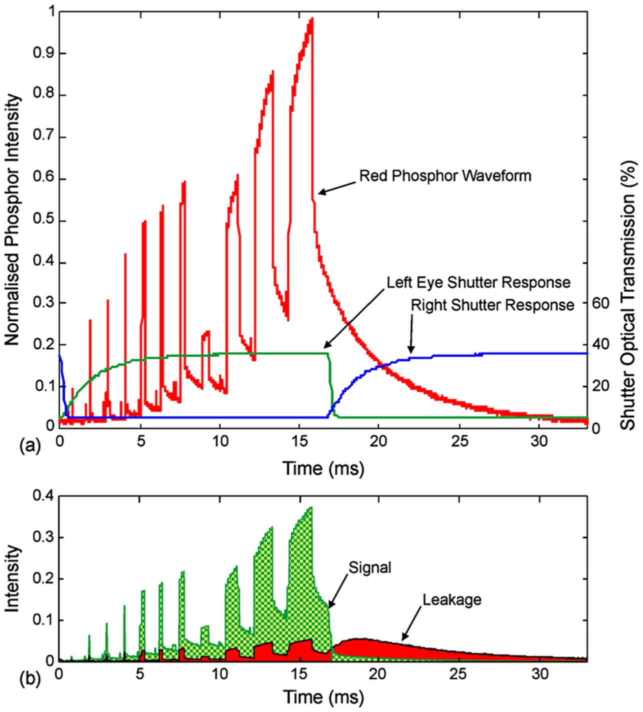

Fig. 11 Timing diagram showing the relative timing of a pair of shutter glasses being used to view a time-sequential 3D image on an example conventional PDP display (a different display than Fig. 10). Part (a) shows the time-domain transmission of the left and right shutters along with the time-domain light output of the display (showing alternating frames of 100% red and black). Part (b) shows the intensity of light through the shutters as will be viewed by the left and right eyes. The desired signal to the left eye through the shutter glasses is shown in hatched green, and the leakage to the right eye through the shutter glasses is shown in solid red.[47] This figure shows severe crosstalk for illustrative purposes and is not intended to be representative of all 3D PDPs.

It should be noted that the examples of Figs. 10 and 11 are derived from older conventional non-3D-Ready PDPs—newer 3D-Ready PDPs will typically exhibit less phosphor persistence and use better shutter glasses than shown in these figures, and also operate at 120 fps with a resultant fewer subframes per frame.

4.1.3 *Time-sequential 3D on LCDs*

Liquid-crystal displays (LCDs) generate an image by backlighting an LCD panel containing an array of individually addressable cells (usually three cells for each pixel—one for each of red, green and blue color primaries). Each LC cell gates the light from the backlight, either passing light, blocking light or somewhere in between for different gray levels. Traditionally, the backlight in LCDs has been based on a cold-cathode fluorescent lamp (CCFL) but light emitting diode (LED) backlights are now increasingly being used. The light source for an LCD projector may be a metal-halide arc lamp, LED, or laser. Conventional LCDs are known as a hold-type display because they output light for the entire frame period.[50]

Figure 12 illustrates the light output of a conventional (non-3D-Ready) LCD monitor driven with a video signal alternating between white and black frames—a common time-sequential 3D test signal. The green line indicates the row of pixels of the display that is being addressed (updated) as time progresses—starting at the top of the screen and scanning down to the bottom in the period of one frame. Looking horizontally from a point on the green line, it can be seen that as each pixel is addressed to change (either from black-to-white, or white-to-black) the pixels at that row take a finite period of time to change from one state to another—this is known as the pixel response time, as discussed in Sec. 4.1 in relation to LC shutters. The scanned image update method of a conventional LCD presents some problems for the use of the time-sequential stereoscopic display method, namely there is no time period available when one frame is visible exclusively across the entire display—this can be seen by referring to Fig. 12 and considering a vertical sector of the graph at a particular time. For example, it can be seen that at 8 ms, the top of the screen will be one frame (white), the bottom of the screen will be the previous frame (black) and a horizontal band in the middle of the screen will be a mix of both frames—this is obviously an unsuitable time to open the shutter. The closest moment to having a single frame visible across the entire screen is at 15 ms, however, there is still some darkening of the display at the very top and bottom (indicating some crosstalk), and additionally this is only for a very short instant (a much longer time period is necessary).[48]

Starting in 2009, a new class of 3D LCD monitors was commercially released which successfully supported the time-sequential 3D method.[55] This was achieved primarily by modifying (increasing the speed of) the image update method—either by increasing the frame rate, or increasing the vertical blanking interval, or both.[48,56–59]

Figure 13(a) illustrates the light output of an example time-sequential 3D LCD monitor or TV using a modified image update method—driven with a video signal alternating between white and black frames. In this figure, the green line (indicating the row of pixels on the display which is being addressed at one point in time) can be seen to complete the full screen update in a much shorter time period, leaving part of the frame-period for the image to stabilize and show a full image across the entire display. For example, in Fig. 13(b), the highlighted period indicates the period when the shutters of a pair of active shutter glasses could be timed to open to

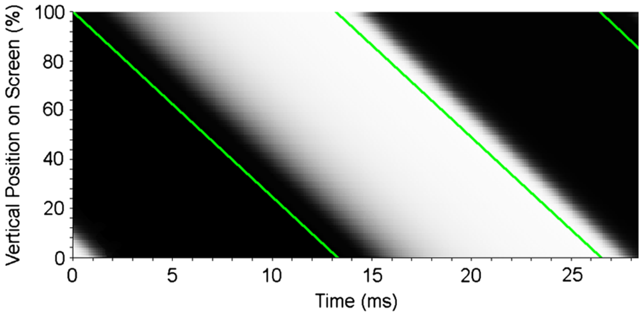

Fig. 12 Time domain response of a conventional LCD monitor with a 4% vertical blanking interval between alternating black and white frames at 85 fps. The vertical axis represents the vertical position on the screen with 100% being the top of the screen and 0% being the bottom of the screen. The green line represents the time at which a particular row of pixels is addressed (updated). It can be seen that there is no time period when a white frame is visible across the entire display (by considering a vertical sector of the graph at a particular time).[48]

present a stereoscopic image, however the gray tinting at the bottom of this area indicates that some crosstalk will still be present. Technologies such as black frame insertion (BFI) and modulated (or scanned) backlight can also be used with LCDs to improve 3D performance.[56]

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

- the performance of the liquid crystal cells in the shutter glasses (see Sec. 4.1);
- the specific timing of the image update method on the screen (see Figs. 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 gray-to-gray);
- the timing of the shuttering of the glasses with respect to the display of images on the screen (see Fig. 13) including the duty cycle of the shutters;
- the particular gray level value of a displayed pixel (pixel response rate varies with the input and output pixel gray level—small changes in gray level often take the longest to complete);[28] 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).[48]

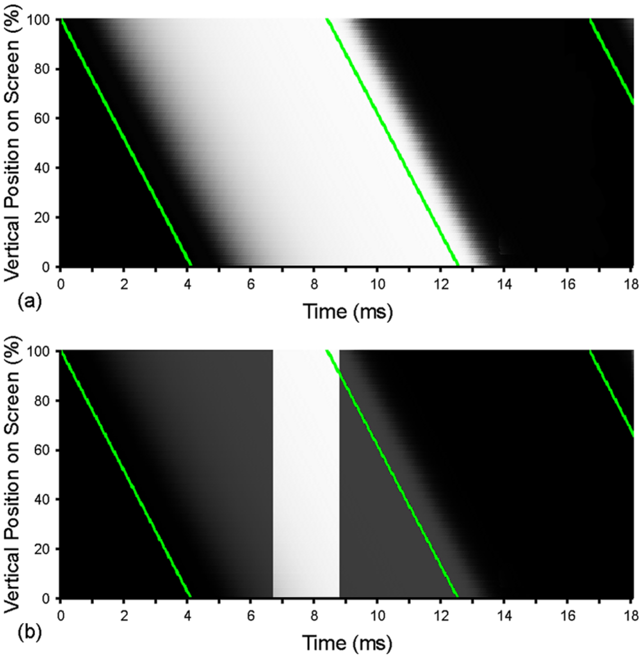

Fig. 13 (a) Time domain response of a simulated time-sequential 3D LCD monitor with a fast addressing rate and fast pixel response rate. Note that the entire screen is updated in only 4.2 ms (the time period of the green line) versus 13 ms with a conventional LCD (Fig. 12). (b) The same monitor as (a) being viewed through shutter glasses with reduced duty cycle switching (the response rate of shutters are not shown).[48] The highlighted period between 6.7 ms and 8.8 ms is almost exclusively white, which means one of the views will dominate, but there is a bit of gray tinting at the bottom of this area, which suggests some crosstalk will be evident at the bottom of the screen.

4.1.4 *Time-sequential 3D on DLPs*

DLP projectors and DLP rear-projection TVs work by shining a light source (e.g., a metal halide arc lamp or LEDs) onto a DMD (digital micro-mirror device—an array of tiny mirrors that can each be individually commanded to tilt ±12° at very fast speeds). 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 color-sequential technique is used to achieve a full-color image[49] as illustrated in Fig. 14. DLPs operate most like a hold-type display—except that gray levels are achieved by a duty cycle modulation process and it is also possible to introduce a blanking interval between frames.[60]

With reference to Fig. 14 it can be seen that the right perspective image is displayed over the period 3 to 8.5 ms with an approximately 3 ms blanking interval before and after the image display period. The blanking interval provides a period during which the left and right shutters in the active shutter glasses can stabilize after state change before light is displayed on the screen for the left and right eyes.

DLPs have very good performance characteristics for time-sequential 3D display—in essence there is no crosstalk introduced by the actual DLP display itself.[49] This is due to two key points: there is no phosphor decay (the DMD mirrors can switch completely from one state to another in ~2 μs),[61] and the entire image changes from one frame to the next at effectively the same time. Crosstalk does not vary with screen position with DLP displays—except where the viewing angle through the shutter 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 performance of the shutter glasses. It is also important that the video electronics path in the DLP display does not mix the left and right images and presents the images in a correct left/right image sequence,[49] but this is now fairly standard with a wide range of 3D DLP projectors and TVs available commercially.

The important factors that cause crosstalk with time-sequential 3D on DLP displays are therefore:

- the performance of the liquid crystal cells in the shutter glasses (see Sec. 4.1),
- the timing (and phase) of the shuttering of the glasses with respect to the image display sequence on the screen (if the LC shutters switch at the wrong time, the glasses can direct images to the wrong eye and hence cause crosstalk), and
- the duration of the blanking interval (the blanking interval should ideally be long enough to hide the transition time of the LC shutters).

4.2 *Polarized 3D Projection*

Polarization is an optical property of light that can be used to encode separate left and right images for presentation to the two eyes of an observer for stereoscopic display purposes.[62] Conceptually, the simplest method of achieving polarized 3D projection involves the use of two projectors, a polarizer fitted to the front lens of each projector, a silvered screen, and matching polarized 3D glasses for the audience. The polarizers can either be linear polarizers or circular polarizers.[62]

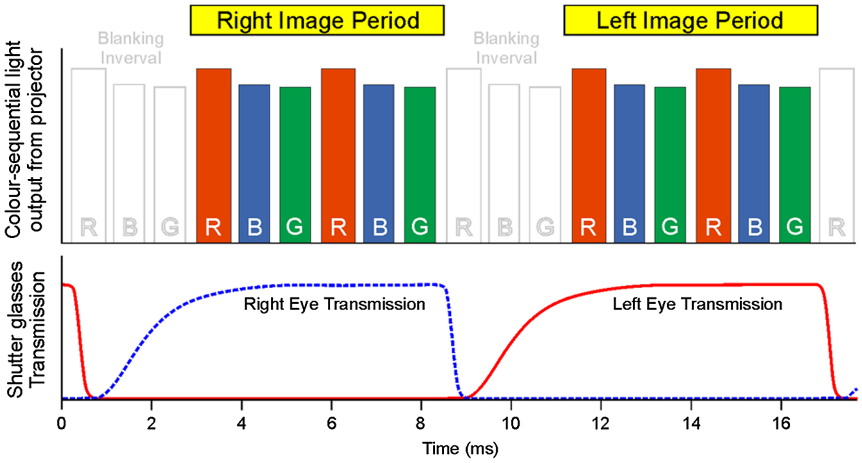

Fig. 14 Illustration of the time-domain performance of an example 120 Hz 3D single-chip digital light projection (DLP) projector. In this figure, a stereoscopic image pair is being presented at 120 frames per second (60 frames for the left and 60 for the right in alternating sequence) and viewed using a pair of shutter glasses. The top of the figure shows the sequence of left and right images built up by a red, blue, green color sequence to construct a full-color image. The bottom half of the figure shows the optical transmission of the shuttering eyewear which must synchronize correctly with the sequence of left and right images. This particular projector is operating with a 6× color cycle speed [6 RGB color cycles per 60 fps frame period (16.7 ms)] and in this case one color cycle per left/right frame period is extinguished to create a blanking interval.

For stereoscopic display purposes the left image channel is encoded with one polarization state, and the right image channel will be encoded with an orthogonal polarization state (for example +45 deg and −45 deg, or 0 deg and 90 deg for linear polarizers; or left-handed and right-handed for circular polarizers). Ideally the left and right image channels will be maintained separately, but due to various limitations of the filters, some leakage will occur between the channels and cause crosstalk.

Polarizing filters are not perfect devices and unfortunately do not perfectly polarize the light that passes through them, which is an avenue for the presence of crosstalk. Figure 15 illustrates the optical performance of an example linear polarizer filter. The key factor to consider for establishing the amount of crosstalk that will be present due to imperfect polarizers is the amount of light that passes through a pair of crossed polarizers [indicated by the transmission crossed (Tc) curve in the figure] compared to the amount of light that passes through a pair of parallel polarizers (Tp in the figure). In this example, the amount of light passed in the crossed polarizer state is very low, which would indicate the potential for very low crosstalk. Figure 16 illustrates the optical performance of an example circular polarizer. In this case, the "double pass reflected" curve provides an indication of the amount of crosstalk to be expected, which is higher than the linear polarizer example of Fig. 15.

These examples are indicated for perfectly orthogonal projection polarizers and perfectly oriented decoding polarizers, however, in a real-life situation the orientation of the decoder polarizers in the glasses may not perfectly match the orientation of the projector polarizers (e.g., due to head tilt or improperly worn glasses) which will adversely affect crosstalk performance.[65] Circular polarizers are less sensitive to rotational misalignment between encoder and decoder polarizers than linear polarizers, but are still adversely affected—the orientation of the rear linear layers must match for optimal performance.

Projection screen properties can also affect crosstalk performance. Different screen materials have different polarized light preservation properties[66] and front projection screens have different polarization performance characteristics compared to rear-projection screens. The quality of the preservation of polarization of light of the screen will affect crosstalk performance.

In summary, the factors which affect crosstalk in dual-projector polarized 3D projection systems are:

- the optical polarization quality of the polarizers,
- the polarization preservation properties of the projection screen, and
- incorrect orientation of the coding or decoding polarizers (perhaps due to head tilt).

Polarized 3D projection can also be achieved time-sequentially with the use of a polarization modulator (as used by StereoGraphics/RealD,[67] NuVision,[68] and DepthQ[69]), or a circular polarization filter wheel (as used by MasterImage[70]). In these systems, the polarization modulator (or filter wheel) is configured to switch between two

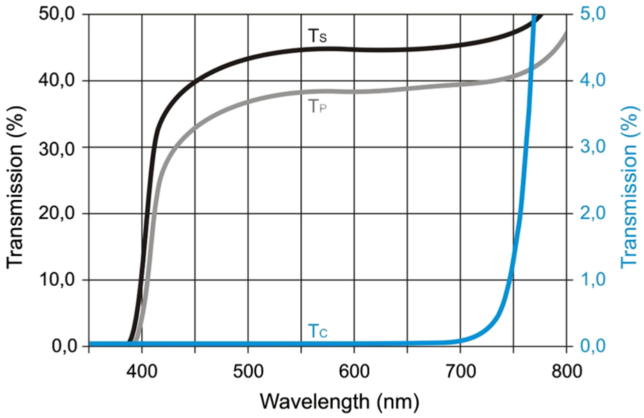

Fig. 15 Spectral response of an example linear polarizer in single Ts, parallel Tp and crossed Tc configurations.[63] The blue "crossed" curve is a close approximation of the amount of leakage that will occur between two linear polarized channels of a polarized stereoscopic display (excluding the effect of head tilt and screen depolarization).

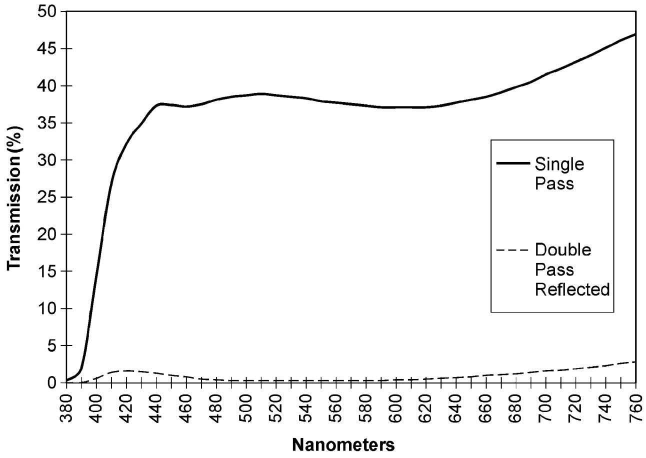

Fig. 16 Spectral response of single and "crossed" circular polarizers.[64] The dashed curve is a representation of the amount of leakage that will occur between two circular polarized channels of a polarized stereoscopic display due exclusively to the polarization quality of the polarizers.

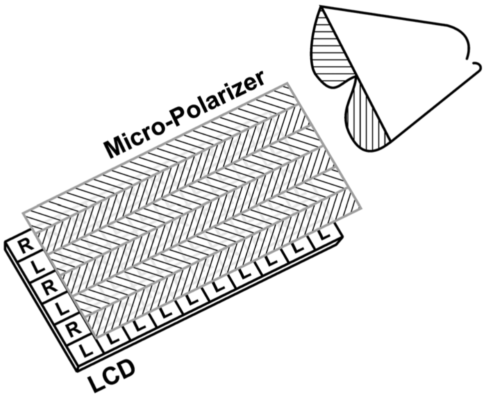

Fig. 17 The optical layout of a micro-polarized 3D LCD. A micropolarizer layer over the front of the LCD polarizes alternate rows of pixels into two different polarization states.[73,74] In this example an observer wearing a pair of polarized 3D glasses will see the odd-numbered rows of pixels through the right eye, and the even-numbered rows of pixels though the left eye.

orthogonal polarization states in synchronization with the sequence of left and right images output by the display. There are two additional factors which can affect crosstalk performance[57,71] in these systems, namely:

- the phase and temporal performance of the polarization modulator with respect to the image sequence of the display, and
- the optical polarization quality of the polarization modulator.

4.3 *Micro-Polarized 3D LCDs*

Micro-polarized 3D LCD monitors (also known as micro-pol, μPol, Xpol, film patterned retarder, or FPR) work by the application of a special optical filter to the front of a conventional LCD panel in order to polarize odd-numbered rows of pixels with one polarization state, and even-numbered rows with the opposite polarization state (see Fig. 17).[72] The two polarization states may either be two orthogonal linear polarization directions, or circular polarization (left-handed circular for one eye and right-handed circular for the other eye)—circular is the most commonly used in commercially available products currently. When the observer wears the appropriate 3D glasses, one eye will see the odd-numbered rows and the other eye will see the even-numbered rows.

Micro-polarized 3D LCD monitors have the advantage that they are viewed using lightweight passive polarized 3D glasses, but have the disadvantage that the vertical spatial resolution per eye is half that of the full display resolution. The construction of a micro-polarized 3D display is illustrated in Fig. 18, where it can be seen that micro-polarizer film is usually applied to the face of the LCD monitor at the viewer side of the LCD optical stack. There is sensitivity of the viewing position of the observer caused by the micro-polarizer film and the LCD cells being separated by a glass layer that is usually approximately 0.5 mm thick. As shown in Fig. 18, if the observer is positioned correctly, the micro-polarizer rows line up correctly with the rows of LCD pixels, however, if the observer were to view the display from a different vertical viewing position, a parallax error would be introduced since the micro-polarizer rows would not correspond correctly with the underlying LCD pixels rows, and hence crosstalk would be introduced. A parallax error also exists if the observer views the display from a different viewing distance. Several methods have been developed to reduce or eliminate the viewing position sensitivity, including the use of a black mask between micro-polarizer strips (this method is usually called *X*-Pol) and in-cell micro-polarization.[75]

With a micro-polarized 3D LCD, the factors that contribute to crosstalk are therefore:

- the optical polarization quality of the micro-polarizer film and hence the polarization quality of the two polarization states;
- the orientation,[65] optical polarization quality, and optical match of the polarized 3D glasses to the output polarization of the display;
- the accuracy of the alignment of the micro-polarizer strips to the rows of pixels on the display;
- the pitch of the micro-polarizer strips relative to the pitch of rows of pixels on the display and the distance between the LCD cells and the micro-polarizer film (usually determined by the thickness of the front glass layer)—which will determine the optimum viewing distance;
- the presence (or absence) of a black mask between micro-polarizer strips—the presence of black mask improves the size of the viewing zones but at the sacrifice of screen luminance;
- the *x*-*y* pixel 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;[17] and
- the horizontal viewing angle of the observer—viewing angles off perpendicular can affect the polarization performance.[77]

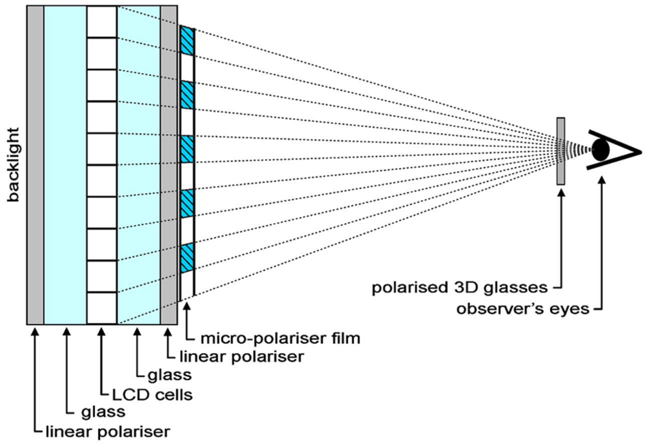

Fig. 18 The side view of a micro-polarized 3D LCD monitor showing the arrangement of the optical layers.[76] It can be seen that the display is sensitive to vertical viewing position since in the indicated viewing position, the micro-polarizer strips line up precisely with the LCD pixels behind them (indicated by the dotted lines), but from a different viewing height the micro-polarizer strips will not optically overlap with the same rows of LCD pixels as the viewing position shown in the diagram, which will lead to crosstalk between the two stereoscopic image channels.

4.4 *Autostereoscopic Displays*

A wide range of technologies are used to achieve autostereoscopic displays (3D without special eyewear). The most common autostereoscopic technologies in current use are based on lenticular[78] and parallax barrier[7] technologies, which both make use of an optical element to direct multiple perspective views in different angular directions out of the display. With reference to Fig. 19, a lenticular autostereoscopic display uses a special lenticular lens sheet containing an array of (usually) vertical column convex lenses placed over the face of the monitor, whereas a parallax barrier autostereoscopic display has a vertical barrier grid (consisting of an alternating series of opaque black vertical strips and clear gaps) placed over the face of the monitor (or in some cases behind the display LCD[79]). If the observer's eyes are located in the correct sweet spots of the display (indicated by the gray diamond shaped polygons in Fig. 19), the observer should be able to see an optimal stereoscopic image across the entire display with minimal crosstalk. If the observer's eyes move away from the sweet spots, a measureable amount of view mixing will occur and this will be visible as crosstalk. Head or eye tracking can be used to steer the views such that the observer's eyes are always in the correct sweet spot, but this is not available with all autostereoscopic displays. In addition to two-view autostereoscopic displays (as illustrated in Fig. 19), multiview autostereoscopic displays are also possible which send out a multitude of views out of the display.[80]

The geometry of the optical element in relation to the display panel will determine the geometry of the view output of the autostereoscopic display, and hence the location of the sweet spots. The properties which determine the view geometry of the autostereoscopic display are the pitch, thickness, curvature and refractive index of the lenticular lens array;[78] the pitch, mounting distance, aperture width, and aperture design of the parallax barrier;[7] all in relation to the display properties of pixel pitch, fill factor, and sub-pixel arrangement. These properties not only determine the location and geometry of the sweet spots but also the amount of crosstalk present in the optimal viewing position(s). Additional factors that can affect crosstalk performance are the general optical quality of the lenticular lens or parallax barrier as well as diffraction[7] and possibly chromatic aberration effects.[81]

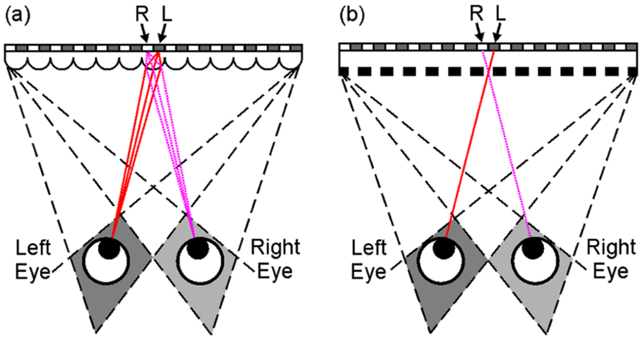

Fig. 19 Example configuration of (a) two-view lenticular autostereoscopic display and (b) two-view parallax barrier autostereoscopic display (top view). The optical elements ideally act to allow the left eye to see only the left image pixels, and the right eye to only see the right image pixels. The 'sweet spots' where this optical isolation works best are shown in gray.

An illustration of the optical output of a lenticular multiview autostereoscopic display is provided in Fig. 20 for an example slanted lenticular multi-view autostereoscopic display.[80] The relative luminance of each view is plotted for a selection of observation positions across the display from a range of viewing positions (simulating a person moving from side to side), at a pre-determined viewing distance. It can be seen in this particular example display the mixing of views is considerable, even at the sweet spot locations, which will be visible as crosstalk.

In summary the important causes of crosstalk in lenticular and parallax barrier autostereoscopic displays are:

- the geometry and optical quality of the optical element (lenticular lens or parallax barrier) including:
- the accuracy of alignment of the optical element to the layout of pixels on the display including the alignment angle of the lens/barrier;
- (for lenticular autostereoscopic displays) the pitch, thickness, curvature and refractive index of the lenticular lens sheet;
- (for parallax barrier autostereoscopic displays) the pitch, mounting distance, aperture width and aperture design of the parallax barrier;
- the pitch, fill factor, and RGB sub-pixel layout of the display;
- the viewing position (in x, y, and z directions) of the observer(s); and
- the x-y pixel 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.

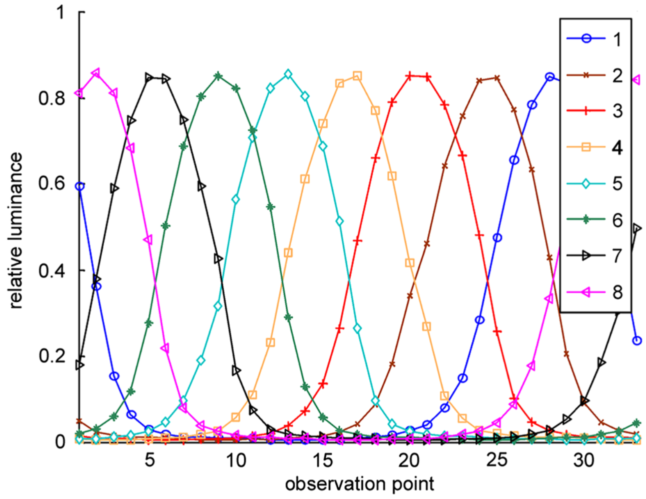

Fig. 20 The visibility of different perspective views as output by an example lenticular multi-view autostereoscopic display when viewed from different horizontally spaced observation points.[80] For example, from viewing position (observation point) 20, view 3 is dominant, but some of views 2 and 4 are also visible which causes crosstalk. This figure shows severe crosstalk for illustrative purposes and is not intended to be representative of all modern autostereoscopic displays.

It has been proposed that some crosstalk is advantageous to the operation of multi-view autostereoscopic displays in order to hide abrupt switches between views when the observer moves from one sweet spot to another.[82] In this case, some crosstalk at view boundaries would be considered desirable, but crosstalk between views at sweet spot locations would be undesirable. This is different to the way crosstalk is considered with other stereoscopic displays, where all crosstalk is usually considered undesirable.

4.5 *Anaglyph 3D*

Anaglyph 3D displays work by coding the left and right image channels into complementary color channels of the display and viewing the display through glasses that have color filters matched to these colors (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. 21.[15] If the spectrum of the display or glasses do not match well, crosstalk will occur. Ideally the spectral output of the display will have a narrow range of light output in the desired spectral range and very little light output out of this region. However, in reality, many displays have spectral output across a broad range of wavelengths—particular in the spectral range dedicated to the other eye. Similarly, in the ideal case, the spectrum transmission of the glasses will pass light in the desired spectral range (which corresponds with the peak output spectral range of the display) and zero transmission immediately out of this range. However, in reality, anaglyph glasses will usually have peak transmission in the desired spectral range with a gradual (slowly changing) reduction in transmission through to a low transmission spectral range which may not totally extinguish light in the undesired spectral range—see Fig. 21(b). These two non-ideal spectral performance aspects will mean that some light from one channel of the display will leak through the filter of the glasses for the other channel and hence lead to crosstalk. There are a range of algorithms that can be used to generate the anaglyph image from a stereoscopic image pair,[83–85] and in some circumstances some image mixing can occur during this stage, which can be interpreted as crosstalk.

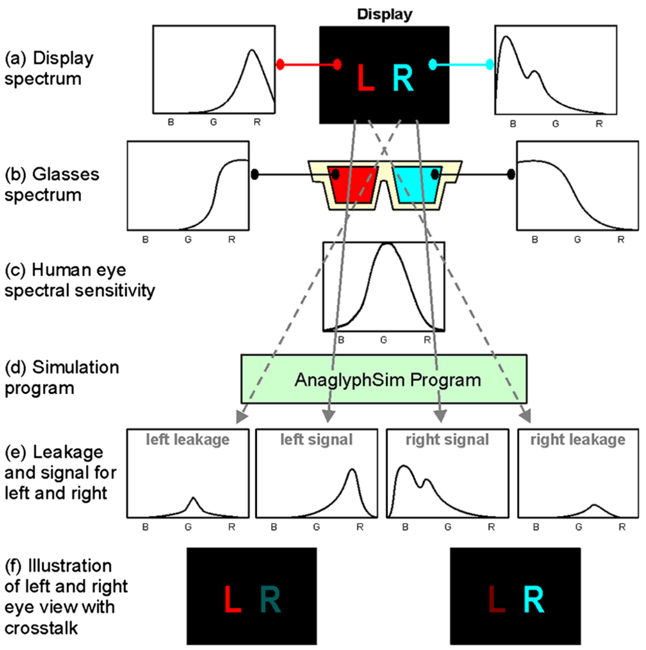

Fig. 21 Illustration of the process (and simulation) of crosstalk in anaglyph 3D displays. From the top: (a) Spectral response of display, (b) spectral response of anaglyph glasses, (c) human eye spectral sensitivity, (d) simulation of crosstalk using a computer program, (e) spectral output characteristic of crosstalk and intended image, and (f) visual illustration of left eye and right eye view with crosstalk.[15]

With anaglyph 3D displays, the important factors that contribute to crosstalk are therefore:

- 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 properties of the anaglyph image generation algorithm.

Crosstalk in anaglyph 3D images generally does not vary with screen position or viewing angle, except where the spectral characteristics of the display or glasses change with viewing angle or screen position. Several papers have analyzed crosstalk in anaglyph 3D images.[15,19,86,87]

The Infitec,[88] Dolby 3D,[89] and Panavision 3D cinema techniques are a special case of anaglyph and can be analyzed in a similar manner.

4.6 *Zero Crosstalk 3D Displays*

Some 3D displays are inherently free of crosstalk. There is no opportunity for image mixing to occur in 3D displays that have completely separate display channels for the left and right eyes. Examples of zero crosstalk 3D displays include the mirror stereoscope (originally developed by Sir Charles Wheatstone in 1838[90]) and some HMDs (head mounted displays).[91] 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%.[33]

4.7 *Non-Display Related Sources of Crosstalk*

It is important to note that crosstalk can also occur in the capture, storage, manipulation and transmission of stereoscopic images prior to arrival at the stereoscopic display. In this case the crosstalk can be caused by the mixing of the left and right images instead of keeping them separate and distinct.

For example, some image crosstalk is possible during stereoscopic image capture using the NuView 3D camera attachment[92] or the prototype 3D lens adapter for the Canon XL-1 video camera.[93] In these examples the crosstalk occurs because the two imaging capture paths share a common optical path before they reach the single imaging sensor and the optical isolation of the two views in this common optical path is not perfect.

Another example is during stereoscopic image manipulation or storage. If a row-interleaved or anaglyph 3D image is stored in JPEG format, the left and right images can become mixed (because JPEG is a lossy compression method), resulting in image crosstalk. This type of crosstalk can be reduced or eliminated by avoiding the use of lossy compression of row-interleaved images, or in the case of anaglyph JPEGs, using the RGB color-space rather than the YUV color-space.[94]

Steps should be taken to avoid crosstalk or image mixing in the stereoscopic source images before they are presented on the stereoscopic display.

5 Measurement of Crosstalk

Two methods exist for the measurement of crosstalk: optical sensors and visual measurement charts.

5.1 *Optical Sensors*

An optical measurement device, such as a photometer or a radiometer, can be used to measure crosstalk. The spectral sensitivity of the sensor(s) used should match the spectral sensitivity of the human visual system (photopic vision) so that the measurements are representative of what a human observer would see.[95–97] Examples of sensors that have been used to measure crosstalk include: Integrated Photomatrix Inc. IPL10530 DAL photo-diode,[46] Ocean Optics USB2000 spectroradiometer,[87] Konica Minolta CS1000 spectroradiometer,[65] Konica Minolta CS-100 spot chroma meter,[20,22] Eldim EZContrastMS,[17] and Photo Research PR-705.[98] Many other devices can also be used for this purpose.

In the first instance, the optical sensor will be placed at the left eye position (either behind the left eye of the 3D glasses, or in the left eye viewing zone for an autostereoscopic display) and a series of measurements taken with a cross-combination of the image channels set at various specified levels. This is then repeated for the other eye position(s). In the case of black-white crosstalk, the two gray-levels will be black and white (see Sec. 2.2.2) and for gray-to-gray crosstalk a much greater number of measurements will be taken for a selection of gray-level combinations (Sec. 2.2.4). Crosstalk may also be characterized spatially across the display,[99,100] or for different horizontal and vertical viewing angles,[14] in which case the number of measurements can increase significantly, resulting in a much more complex crosstalk dataset—in which case the automation of the taking of the measurements can be advantageous.

Efforts to standardize crosstalk measurement methods are currently under way and being published by ICDM,[14] IEC, ISO, and others.[4,27] Ensuring the accuracy and reproducibility of crosstalk measurements between different measurement sensors, measurement methods and laboratories is an important problem and work is continuing in this area.[99,101,102]

5.2 *Visual Measurement Charts*

Visual measurement charts provide a very quick and effective way of evaluating crosstalk in a stereoscopic display without the need for expensive optical test equipment. Two examples of such charts are shown in Figs. 22 and 23. 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 gray level ramp.

Unfortunately, there are some limitations with 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), (c) the chart only measures white-to-black crosstalk, and (d) 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 to quantify crosstalk when accurate crosstalk data are needed that are not subject to the possible inaccuracies described above.

6 Crosstalk Reduction

In order to reduce the amount of crosstalk present on a particular stereoscopic display, it is necessary to reduce the effect of one or more of the crosstalk mechanisms of that particular display (as described in Sec. 4). First, 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 is necessary to perform a detailed analysis and optical measurement of the display and glasses in the temporal, spatial, and spectral domains. It is also beneficial to develop a simulation of crosstalk on a 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 Sec. 8).

Once the relative contributions of each crosstalk mechanism are known, the main causes of crosstalk should be assessed 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 changes made to reduce crosstalk. In some cases the trade-off might be increased cost of manufacture of the display or glasses, or a reduction in some other display performance characteristic. There will probably be an optimum balance between crosstalk and other display performance characteristics (including cost of manufacture,

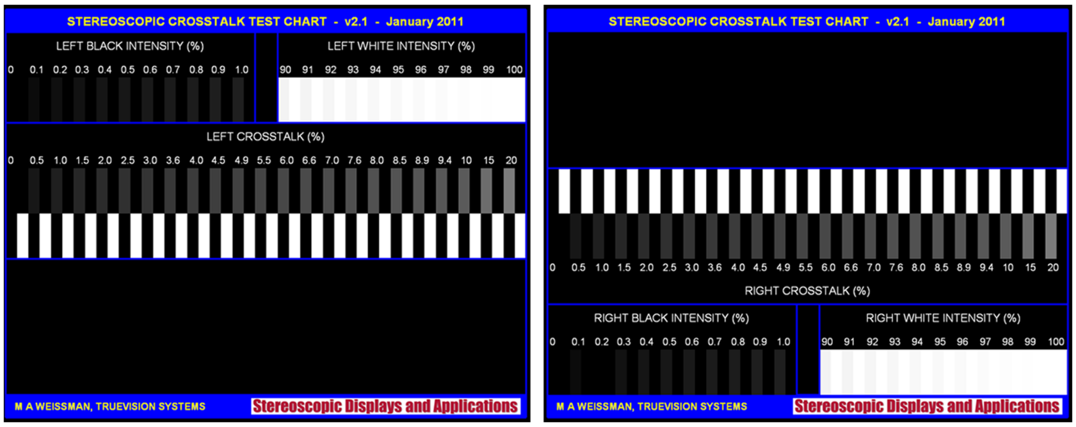

Fig. 22 Crosstalk measurement test chart designed by Weissman.[103]

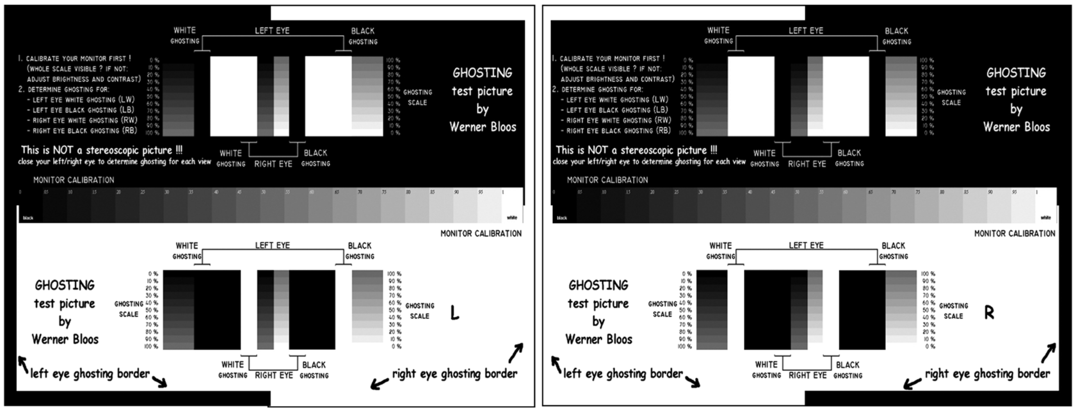

Fig. 23 Crosstalk measurement test chart designed by Bloos.[104]

flicker, luminance, contrast, black level, etc.). For example, with the conventional plasma displays tested in Ref. 47, the study suggested using shorter persistence phosphors in plasma displays—but this might result in the increased cost or reduced luminance of the display. With time-sequential 3D on LCDs, a reduction in the duty cycle of the shutter glasses could reduce crosstalk, but this might be at the cost of reducing the image luminance.[48] With micro-polarized 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 reduce the luminance of the display and possibly increase the cost of manufacture.

Some crosstalk reduction methods may only be possible to be performed by the display manufacturer (requiring a fundamental change to the display hardware), whereas other techniques might be able to be performed by the user (for example fine-tuning the timing of the glasses).

Another way to reduce the visibility of crosstalk (ghosting) is to reduce the contrast ratio of the image or display and/or reduce the luminance of the display (see Sec. 3)—but both of these actions would also reduce the overall quality of the displayed image and fundamentally this does not actually reduce the crosstalk, just the visibility of the crosstalk. Crosstalk cancellation is another way of reducing the visibility of crosstalk and is discussed in the next section.

7 Crosstalk Cancellation

Crosstalk cancellation (also known as anti-crosstalk, crosstalk compensation or ghost-busting) can be used to reduce the visibility of crosstalk.[105–107] When crosstalk cancellation is used, the crosstalk is still present but it is concealed by the cancellation process.

Crosstalk cancellation involves the pre-distortion of the stereoscopic image in a specially controlled manner before display. A simple example of the process of crosstalk cancellation is illustrated in Fig. 24. Part (a) shows the leakage of the right image (unintended) channel into the left-eye view in a system without crosstalk cancellation. Part (b) shows the crosstalk cancellation process—the amount of leakage that is expected to occur from the right channel to the left channel is evaluated and this amount is subtracted from the left image creating a modified left image (shown as anti-crosstalk in the figure). When the modified left image is displayed on screen and viewed, the addition of the modified left image plus the leakage from the right image results in the equivalent of the original left image (since the anti-crosstalk and the leakage cancel each other out).

A simple illustration of the process of crosstalk cancellation on a stereoscopic display. (a) An example of a stereoscopic image with crosstalk visible to the left eye from the leakage of light from the right image channel. (b) An example of anti-crosstalk being applied to the left image so that

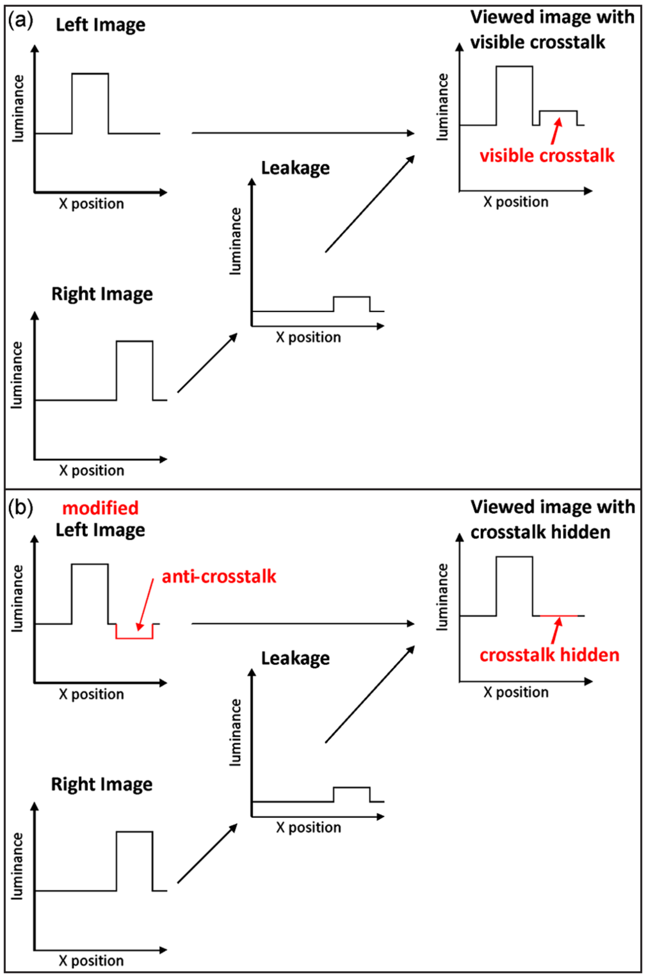

Fig. 24 A simple illustration of the process of crosstalk cancellation on a stereoscopic display. (a) An example of a stereoscopic image with crosstalk visible to the left eye from the leakage of light from the right image channel. (b) An example of anti-crosstalk being applied to the left image so that when leakage occurs from the right image channel, it cancels with the anti-crosstalk to hide the crosstalk.

when leakage occurs from the right image channel, it cancels with the anti-crosstalk to hide the crosstalk.

In practice, the full crosstalk cancellation process is more complicated than this simple explanation—a more detailed algorithm will normally be used which includes an inverse-transformation of crosstalk[106] and consideration of psychovisual effects,[106] pixel position,[105] display gamma,[108] previous-frame content,[109] and black-level adjustment.[110,111]

Crosstalk cancellation has been evaluated for a wide range of stereoscopic display technologies, including anaglyph,[107,112] polarized projection,[108,113] and time-sequential 3D on CRTs,[105,106] PDPs,[52,114] and LCDs.[57,115]

In most stereoscopic displays, crosstalk is primarily an additive process (the leakage adds to the intended signal), however, as mentioned in Sec. 5.1, the crosstalk process in time-sequential 3D LCDs is quite different—it is highly nonlinear and is a mix of additive and subtractive (in some instances the leakage subtracts from the intended signal).[21] In this instance the crosstalk cancellation algorithm will need to be much more complicated and multi-dimensional and may be more easily implemented using a look-up table.[21,99,106]

Crosstalk cancellation has limitations—one particular challenge is with high contrast images containing bright details against a black or dark background. If anti-crosstalk is applied to a black or dark background, it may require the modified image to go darker than black (i.e., negative), which is not possible with current displays. In this situation, one solution is to raise the black level of the image to accommodate the level of anti-crosstalk that is needed, but this will reduce image contrast and may give the image an undesirable washed-out look.[105,106,110,111]

Crosstalk cancellation works best when the amount of crosstalk that needs to be cancelled is already relatively small. Large amounts of crosstalk may not be able to be fully 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[22] or head tilt, or when the crosstalk is not pixel-aligned in both views—as occurs with micro-polarized 3D LCDs.

8 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 performing 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 new design of 3D glasses is used. Hundreds or thousands of what-if scenarios can be simulated at minimal expense allowing new crosstalk reduction scenarios to be easily explored.

In order to develop a crosstalk simulation algorithm it is necessary to perform an optical measurement of the display and glasses in the temporal, spatial, and spectral domains. The accuracy of the crosstalk model will also need to be validated. Crosstalk simulations for parallax barrier 3D,[7] anaglyph 3D,[15,19,87] and time-sequential 3D on CRT,[46] PDP,[47] and LCD[56] have been developed.

9 Conclusion

This paper has provided a review of knowledge about stereoscopic display crosstalk with regard to terminology, definitions, mechanisms, measurement, and minimization. Crosstalk is a very important attribute in determining image quality in stereoscopic displays. In order for the stereoscopic display field to grow it is important that there be a common understanding of crosstalk. This field is still evolving and several efforts are currently under way to provide standardized methods of defining and measuring crosstalk[4,27]—one of which has recently been released.[14] Ultimately we want stereoscopic displays with low levels of crosstalk and in order to meet this goal, display designers will need to minimize the various crosstalk mechanisms described in this paper. Currently, crosstalk is not a specification that is regularly released by display manufacturers, but it is hoped that in the near future this important determinant of stereoscopic display quality will be readily available (along with which definition has been used to calculate it)—this will empower consumers to be able to intelligently choose 3D displays with lower crosstalk and hence better 3D image quality.

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