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User-friendly minimization technology of three-dimensional crosstalk in three-dimensional liquid crystal display televisions with active shutter glasses

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Abstract. We propose a new three-dimensional (3-D) crosstalk minimization method for the active shutter glasses-type 3-D liquid crystal displays (LCD) television (TV). The crosstalk was reduced from 43% to 10% on average with the proposed technology. Furthermore, we propose a user-friendly method to reduce the 3-D crosstalk without any measurement equipment, which enables consumers to make their TVs crosstalk free. It is found that the results of the proposed crosstalk minimization method and user-friendly method are matched well. Thus, 3-D TV consumers can easily minimize the 3-D crosstalk with their eyes only. © 2012 *Society of Photo-Optical Instrumentation Engineers (SPIE).* [DOI: 10.1117/1.OE.51.10.107401]

Subject terms: three-dimensional TV; crosstalk; overdrive; active shutter glasses; liquid crystal display.

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1 Introduction

In recent years, the three-dimensional (3-D) display market has grown worldwide. The advanced 3-D display technology and various 3-D contents have brought market expansion. Since 3-D displays provide a realistic experience to the television (TV) audience, consumers are continuously increasing. Most 3-D TVs are stereoscopic 3-D TVs. The stereoscopic 3-D display expresses three-dimensional images by two-dimensional images of the left and right eyes. They require special glasses, such as active shutter or polarized glasses. As 3-D TV consumers remarkably increase, visual fatigue problems[1–3] of stereoscopic 3-D TVs begins to draw a lot of attention. The discrepancy between the accommodation and convergence of human eyes has been known as one of main root causes of the problems.[4,5] One of the most serious problems is a 3-D crosstalk phenomenon. As shown in Fig. 1, when a 3-D image is displayed on the 3-D TV, there is a spatial difference between the left and right eye images. These two images are displayed at slightly different positions on the screen but not at the same position. Thus, when the left eye sees the left image as well as a weak overlapped right image or vice versa, the 3-D crosstalk can occur around the boundaries of objects.

The 3-D crosstalk is widely studied in various respects. Many mathematical methods to quantify the phenomenon have been suggested by comparing the luminance of the ghost images with those of the original images.[6–14] The definition of the crosstalk ratio considering an observer's perception has been also proposed.[15] A compensation algorithm and simulation model of 3-D crosstalk of plasma display panels has been studied.[16,17] Most 3-D TVs for home applications adopt liquid crystal displays (LCDs). Thus, it is necessary to investigate the 3-D crosstalk by considering unique characteristics of LCDs.

In this paper, the crosstalk of 3-D LCD TVs is analyzed. The slow response of LC molecules is investigated. To solve the crosstalk, this paper proposes a method that applies the overdrive (OD) technology commonly used to improve LC response.[18–23] Any technologies should be user-friendly. This study focuses on how to make the technology for people to use.

In the following section, the crosstalk of 3-D LCD is analyzed, and then the crosstalk minimization algorithm is suggested in Sec. 3. In Sec. 4, a new method to reduce the crosstalk by the consumers is proposed. Finally, in Sec. 5, the conclusion of this study is drawn.

2 3-D Crosstalk Analysis

In order to analyze the 3-D crosstalk, it is necessary to understand the driving scheme for 3-D LCD TVs. A commercial 46-inch full-HD (1920×1080) 3-D LCD TV is used for our experiments. Figure 2 shows a basic driving scheme for the 3-D LCD TV that uses active shutter glasses (SG). This driving scheme adopts the black frame insertion (BFI). The black data are inserted to separate left eye images from right eye images. One frame ($1/60$ s) in the conventional two-dimensional (2-D) driving scheme corresponds to four fields in 3-D driving, and each field is $1/240$ s long. All data are refreshed every $1/240$ s. The left image is displayed for $1/240$ s, and then the full-screen black image is inserted at the next field. Subsequently, the right image is displayed for $1/240$ s and then the black image is displayed again at the last field. Thus, the data sequence during $1/60$ s is left-black-right-black (L-B-R-B). The active SG transmit the left and right images synchronized to displayed images on the LCD panel.

Figure 3(a) shows the measured optical responses to understand crosstalk phenomenon in active SG-type 3-D LCD panels. Figure 3(b) shows how to measure the luminance responses. The luminance response was measured by using a photodiode. When light comes into the photodiode, the photocurrent is generated through the photodiode. Then, the photocurrent is amplified by the transistor. The luminance response is obtained by measuring the voltage across the resistor through which the amplified photocurrent flows. As shown in Fig. 3(a), the red and blue lines are the

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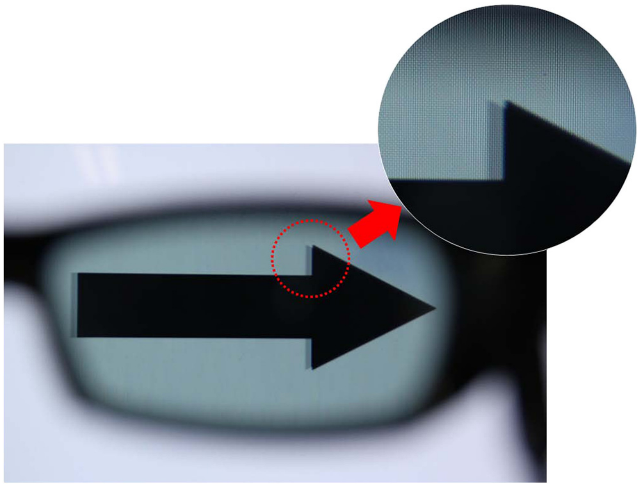


Fig. 1 The photograph of the 3-D crosstalk taken through shutter glasses.

luminance responses when the image data sequence of G1-B-G1-B and G2-B-G1-B are applied, respectively. The red solid line data were measured when the left image data were the same as right ones. The blue dashed line data were measured when left image data were different from the right ones. When the gray levels of G2 and black are successively applied following G1 and black (blue dashed line), the black level at the 2nd frame cannot reach the same black luminance as that of red line as shown in Fig. 3(a). In addition, at the 3rd frame in Fig. 3(a), the luminance of G1 (blue dashed line) is also different from that of red solid line even though G1 is identically applied for both cases. This result indicates that the previous frame data affects the next frame data, and the next frame data cannot reach its target level within a field time (1/240 s). This is caused by the slow response of LC molecules. This luminance response is mainly related to the 3-D crosstalk. When users see a static 3-D image on the 3-D TV, the actual image data shows temporal changes. Thus, the left eye can observe the abnormal image affected by the previous right eye image, which is called the crosstalk.

A new simple pattern is suggested to analyze how users perceive the crosstalk, as shown in Fig. 4. In Fig. 4(a), the left-half part represents a left eye image, and the right-half part shows a right eye image for 3-D driving. The gray levels of background (A) and box (B) are G1 and G2, respectively. The only difference between the left and right half parts is the gray levels of X and Y area. The gray level of X is the same as that of the background, but the gray level of Y is displayed the same as that of the box. Figure 4(b) shows the displayed image on the screen in 3-D mode when the image shown in Fig. 4(a) is the input. The data sequence of the background becomes G1-B-G1-B (L-B-R-B). The sequence of the box is G2-B-G2-B (L-B-R-B). However, it should be noted that X/Y region has the data sequence of G1-B-G2-B (L-B-R-B). The crosstalk can be observed in this pattern when users see the X/Y region through the SG. Figure 4(c) shows the photographs of the crosstalk phenomenon at the X/Y region taken through left and right glasses. Ideally, the brightness of the background image (A) must be the same as that of X when it is seen through the left glass. However, the brightness of A and X look different from each other. The brightness of X is brighter than that of A. It is because the left eye image is affected by the bright box of right eye image (B). On the contrary, in the case of the right eye image, the brightness of Y is darker than that of the box image (B) because the right eye image is influenced by the left eye image.

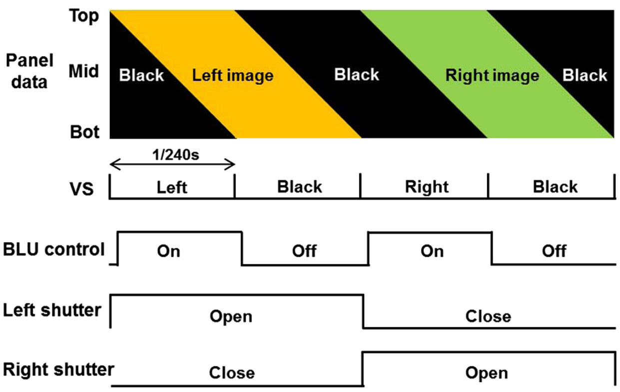
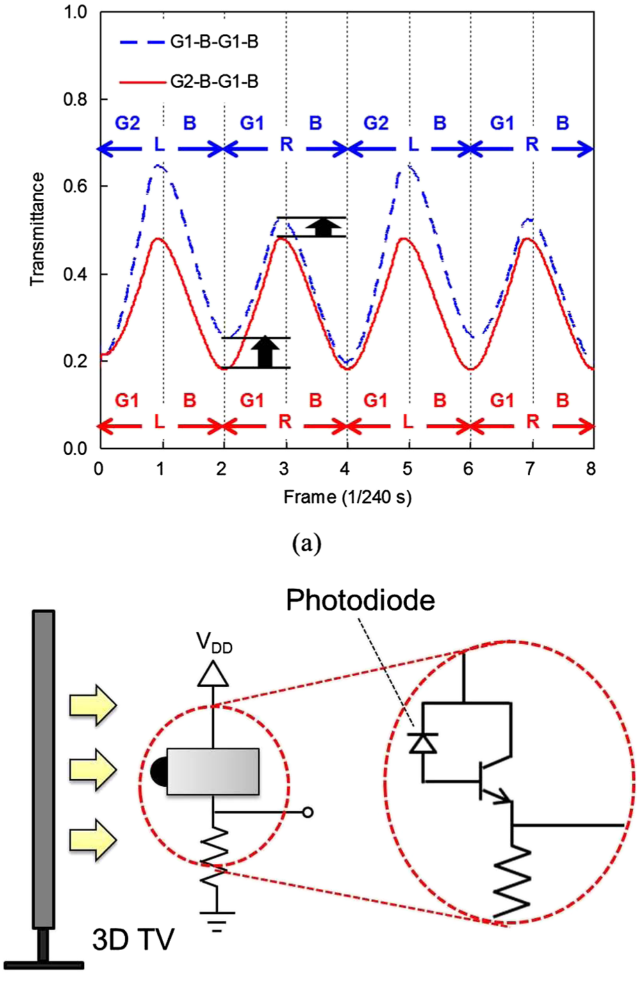


Fig. 2 Driving scheme of a commercial 3-D LCD TV that uses active shutter glasses.



(a)

(b)

Fig. 3 (a) Optical responses to describe the crosstalk phenomenon in shutter glass-type 3-D LCD. (b) How to measure the luminance responses.

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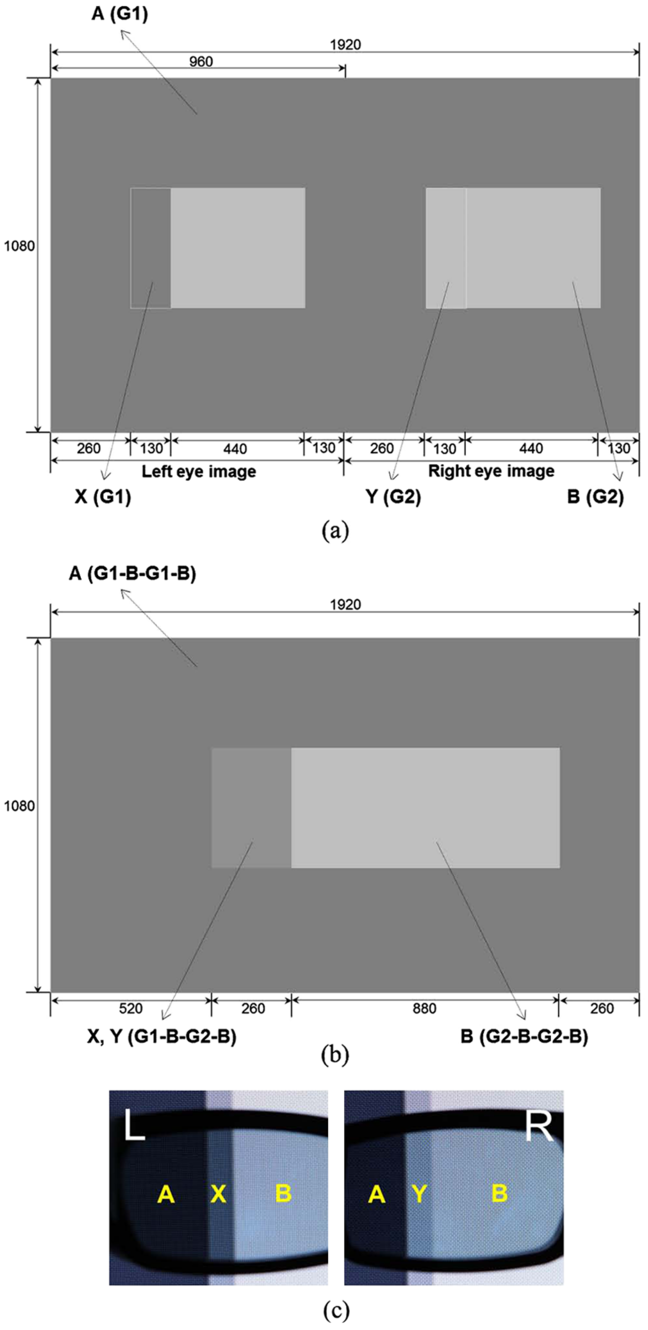

Fig. 4 Pattern for the analysis of the crosstalk in SG 3-D LCD. (a) During 2-D driving (area of $X = $ area of Y). (b) During 3-D driving. (c) Actual photos of the crosstalk phenomenon captured in Fig. 4(b).

As described above, the slow response of LC molecules causes this crosstalk. The X/Y region cannot reach a certain target level or black level in $1/240$ s. The left and right eye images must be shown separately. In the following section, a new method to reduce the crosstalk is proposed.

3 New Method for Crosstalk Minimization

To solve the crosstalk, we propose a method that applies the OD technology commonly used to improve LC response. Figure 5 shows the concept of the OD technology, where G_N is an input gray level and L_N is the target luminance of G_N.[24] As shown in Fig. 5(a) and 5(b), LC responses of transitions from G_1 to G_2 and G_1 to G_3 do not reach the target levels L_2 and L_3 in a frame time ($1/60$ s), respectively. We can see that the LC response of the transition from G_1 to G_3 reaches L_2 which is the target luminance of G_2, after one frame time as shown in Fig. 5(b). Thus, we can get an ideal luminance response for the transition from G_1 to G_2 if we change the data sequence to be $G_1 \rightarrow G_3 \rightarrow G_2$ rather than $G_1 \rightarrow G_2 \rightarrow G_2$ as shown in Fig. 5(c). Here, G_3 is the OD value of the transition from G1 to G2. In this paper, we use these OD values to solve the crosstalk.

Figure 6(a) illustrates a proposed pattern to minimize the crosstalk. In this pattern, the values of $\mathrm{OD}_{2\rightarrow 1}$ and $\mathrm{OD}_{1\rightarrow 2}$ of the left and right half parts represent the image data of the left and right eye images in the 3-D mode, respectively. $\mathrm{OD}_{2\rightarrow 1}$ and $\mathrm{OD}_{1\rightarrow 2}$ are controlled individually. In the 3-D mode, the data sequence of the image is $\mathrm{OD}_{2\rightarrow 1} - B - \mathrm{OD}_{1\rightarrow 2} - B$ (L-B-R-B). We should adjust $\mathrm{OD}_{1\rightarrow 2}$ and $\mathrm{OD}_{2\rightarrow 1}$ to enable luminance to reach the target level in $1/240$ s (one field time). $\mathrm{OD}_{1\rightarrow 2}$ is an OD value for the transition from G1 to G2, and $\mathrm{OD}_{2\rightarrow 1}$ represents an OD value required for the transition from G2 to G1. Figure 6(b) shows a flowchart of the proposed method. At first, an input image becomes a full screen gray level G1. The data sequence of the displayed image is G1-B-G1-B in the 3-D mode. Then, the luminance of the screen through the left shutter glass is measured. At this step, the measured luminance is defined as a reference luminance value of G1, $L_{\mathrm{ref}}(G1)$. Then, the input is changed to a full screen image with gray level G2 and the luminance is measured through the right shutter glass ($L_{\mathrm{ref}}(G2)$). After measuring two reference luminance values, the input image is changed as shown in Fig. 6(a). Initial values of $\mathrm{OD}_{2\rightarrow 1}$ and $\mathrm{OD}_{1\rightarrow 2}$ are G1 and G2, respectively. $\mathrm{OD}_{1\rightarrow 2}$ is adjusted and the luminance of the screen is measured through the left shutter glass ($L(\mathrm{OD}_{1\rightarrow 2})$). If $L(\mathrm{OD}_{1\rightarrow 2})$ is equal to $L_{\mathrm{ref}}(G2)$, fix the $\mathrm{OD}_{1\rightarrow 2}$ value. Then, adjusting $\mathrm{OD}_{2\rightarrow 1}$ and measuring the luminance of the screen ($L(\mathrm{OD}_{2\rightarrow 1})$) through the right shutter glass is repeated until it becomes the same as $L_{\mathrm{ref}}(G1)$. In this way, both $\mathrm{OD}_{2\rightarrow 1}$ and $\mathrm{OD}_{1\rightarrow 2}$ are selected. However, it should be noted that $L(\mathrm{OD}_{1\rightarrow 2})$ may not be the same as $L_{\mathrm{ref}}(G2)$ after $\mathrm{OD}_{2\rightarrow 1}$ is adjusted. The luminance change caused by the newly adjusted $\mathrm{OD}_{2\rightarrow 1}$ affects $L(\mathrm{OD}_{1\rightarrow 2})$ again. The two conditions of $L(\mathrm{OD}_{2\rightarrow 1}) = L_{\mathrm{ref}}(G1)$ and $L(\mathrm{OD}_{1\rightarrow 2}) = L_{\mathrm{ref}}(G1)$ need to be satisfied, simultaneously. Adjustments and measurements need to be repeated until they meet the conditions. After finding appropriate $\mathrm{OD}_{1\rightarrow 2}$ and $\mathrm{OD}_{2\rightarrow 1}$ values to satisfy both conditions, the two OD values are stored.

Table 1 shows an example of the work flow proposed in Fig. 6(b). Table 1 shows the OD values and luminance at each step that is shown in Fig. 6(b) when G1 and G2 were gray levels 64 and 128, respectively. In this example, $L_{\mathrm{ref}}(64)$ was $1.27\ \mathrm{cd/m^2}$ and $L_{\mathrm{ref}}(128)$ was $10.64\ \mathrm{cd/m^2}$. At the step (0), as numbered in Fig. 6(b), $\mathrm{OD}_{2\rightarrow 1}$ and $\mathrm{OD}_{1\rightarrow 2}$ were initialized. However, $L(\mathrm{OD}_{2\rightarrow 1})$ and $L(\mathrm{OD}_{1\rightarrow 2})$ are not equal to $1.27\ \mathrm{cd/m^2}$ and $10.64\ \mathrm{cd/m^2}$, respectively, which means adjustment of OD values is required. Thus, $\mathrm{OD}_{1\rightarrow 2}$ was adjusted to 155 to make $L(\mathrm{OD}_{1\rightarrow 2}) = L_{\mathrm{ref}}(128)$ at the step (1). After the first adjustment, $L(\mathrm{OD}_{2\rightarrow 1})$ changed to $4.10\ \mathrm{cd/m^2}$ which was not equal to $L_{\mathrm{ref}}(64)$ because $\mathrm{OD}_{1\rightarrow 2}$ varied from 128 to 155. At the step (2), $\mathrm{OD}_{2\rightarrow 1}$ was fixed to 23 to satisfy $L(\mathrm{OD}_{2\rightarrow 1}) = L_{\mathrm{ref}}(64)$. Through three iterations, the final $\mathrm{OD}_{2\rightarrow 1}$ and $\mathrm{OD}_{1\rightarrow 2}$ became 14 and 187, respectively.

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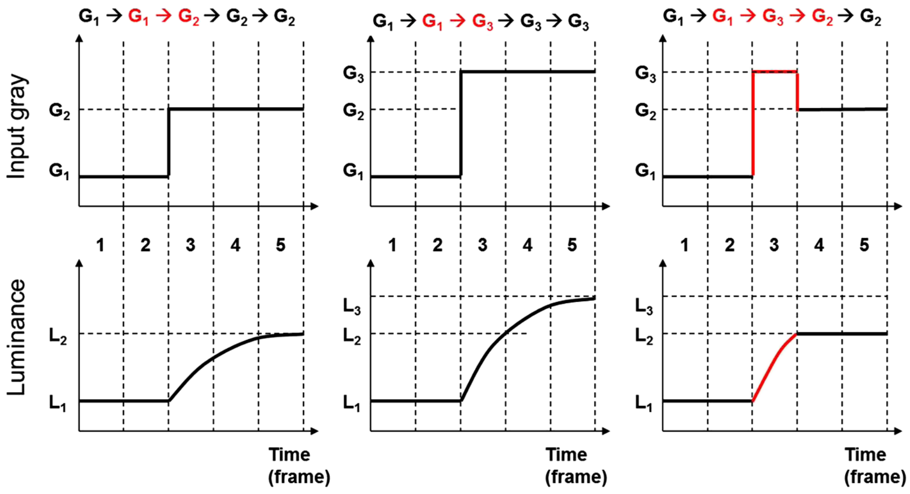

(a) (b) (c)

Fig. 5 The concept of the overdrive technology. (a) Luminance response of the transition from G1 to G2, (b) luminance response of the transition from G1 to G3, and (c) luminance response when overdrive is applied.[24]

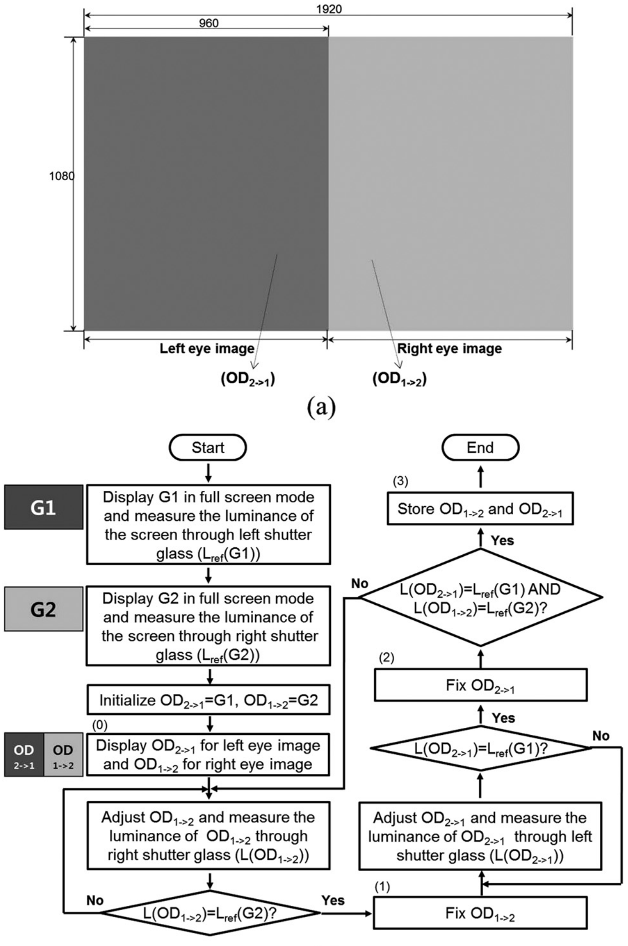

Fig. 6 (a) Proposed pattern to find the values to minimize the crosstalk. (b) Flowchart of the proposed method.

Figure 7 shows a look-up table (LUT) extracted from the proposed method. If one measurement is conducted, two OD values can be obtained. In the example of Table 1, two OD values extracted are 187 which is located where G1 is 64 and G2 is 128 (red dashed line), and 14 located where G1 is 128 and G2 is 64, reversely (blue dashed line). Thus, when the original data sequence is 128-B-64-B (L-B-R-B), the adjusted data sequence is 187-B-14-B (L-B-R-B). In the case of 64-B-128-B (L-B-R-B), the adjusted data sequence is 14-B-187-B (L-B-R-B). Figure 8 shows the comparison results of the crosstalk[25,26] before and after application of the proposed method. The definition of the 3-D crosstalk is given as follows:

$$\mathrm{CT}_{i,j} = \left| \frac{L_{i,j} - L_{i,i}}{L_{j,i} - L_{i,i}} \right| \times 100(\%). \tag{1}$$

$\mathrm{CT}_{i,j}$ represents the 3-D crosstalk of gray level i affected by gray level j. $L_{i,j}$ means the luminance of the gray level i influenced by that of the gray level j. On the contrary, $L_{i,j}$ is the luminance of the gray level j affected by the gray level i. Thus, $L_{i,j}$ is the luminance of i-th gray images which is used as the reference luminance for comparison. All the luminance values in Eq. (1) are measured through the SG. As plotted in Fig. 8, the crosstalk is approximately 43% on average without compensation, but drops to 10% on average with the proposed algorithm. The crosstalk is remarkably decreased for all gray levels by the proposed method.

4 User-Optimized Crosstalk Minimization

It is believed that the new proposed method can remarkably reduce the crosstalk in 3-D LCD TVs. However, the consumers are not familiar with finding accurate OD values described in Sec. 3. The user needs to have a deep understanding of LCD characteristics, and expensive measurement equipment. This study provides a way for common people to use the proposed method by themselves without any cost increase.

Figure 9(a) shows the 2-D input image in the software developed for a user-friendly technique for crosstalk

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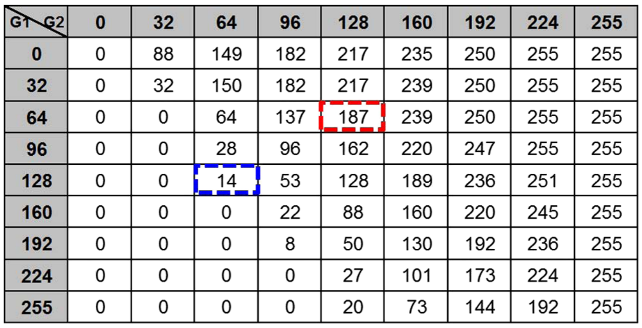
Table 1 Overdrive values and luminance at each step.

Step	$OD_{2\to1}$	$OD_{1\to2}$	$L(OD_{2\to1})$ (cd/m^2)	$L(OD_{1\to2})$ (cd/m^2)
(0)	64	128	2.97	6.55
(1)	64	155	4.10	10.64
(2)	23	155	1.27	6.76
(1)	23	178	1.84	10.64
(2)	16	178	1.27	9.42
(1)	16	185	1.40	10.64
(2)	14	185	1.27	10.07
(3)	14	187	1.27	10.64

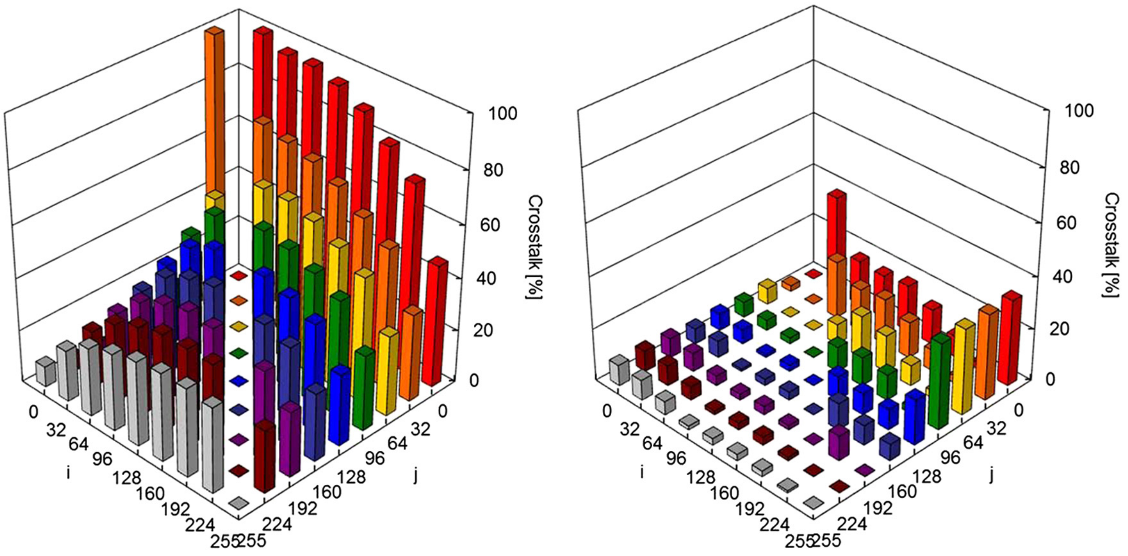
In the above example, $G1 = 64$, $G2 = 128$, $L_{ref}(64) = 1.27\ cd/m^2$, and $L_{ref}(128) = 10.64\ cd/m^2$.



G1 \ G2	0	32	64	96	128	160	192	224	255
0	0	88	149	182	217	235	250	255	255
32	0	32	150	182	217	239	250	255	255
64	0	0	64	137	187	239	250	255	255
96	0	0	28	96	162	220	247	255	255
128	0	0	14	53	128	189	236	251	255
160	0	0	0	22	88	160	220	245	255
192	0	0	0	8	50	130	192	236	255
224	0	0	0	0	27	101	173	224	255
255	0	0	0	0	20	73	144	192	255

Fig. 7 Look-up table extracted from the proposed algorithm.

minimization. Users can control the gray levels of background (A), box (B), X, and Y region. Figure 9(b) shows the displayed image on the LCD screen in the 3-D mode when the input image is as shown in Fig. 9(a). The gray levels of the background (A) and the box (B) are G1 and G2, respectively. The gray levels of X and Y are $OD_{2\to1}$ and $OD_{1\to2}$, respectively. Figure 9(c) shows the flowchart of the new proposed method. A subject should wear shutter glasses. The 3-D TV should be in the 3-D mode. At first, the subject selects the gray levels of background (G1) and box (G2). Then, $OD_{2\to1}$, and $OD_{1\to2}$ are initialized to G1 and G2, respectively. After initialization, the subject opens their left eye and closes their right eye. In the next step, the subject adjusts $OD_{2\to1}$ until the brightness of X in Fig. 9(b) is the same as that of A in Fig. 9(b). If a proper $OD_{2\to1}$ value is found, the subject opens their right eye and closes their



(a) (b)

Fig. 8 The comparison results of the crosstalk (a) before and (b) after application of the proposed algorithm.

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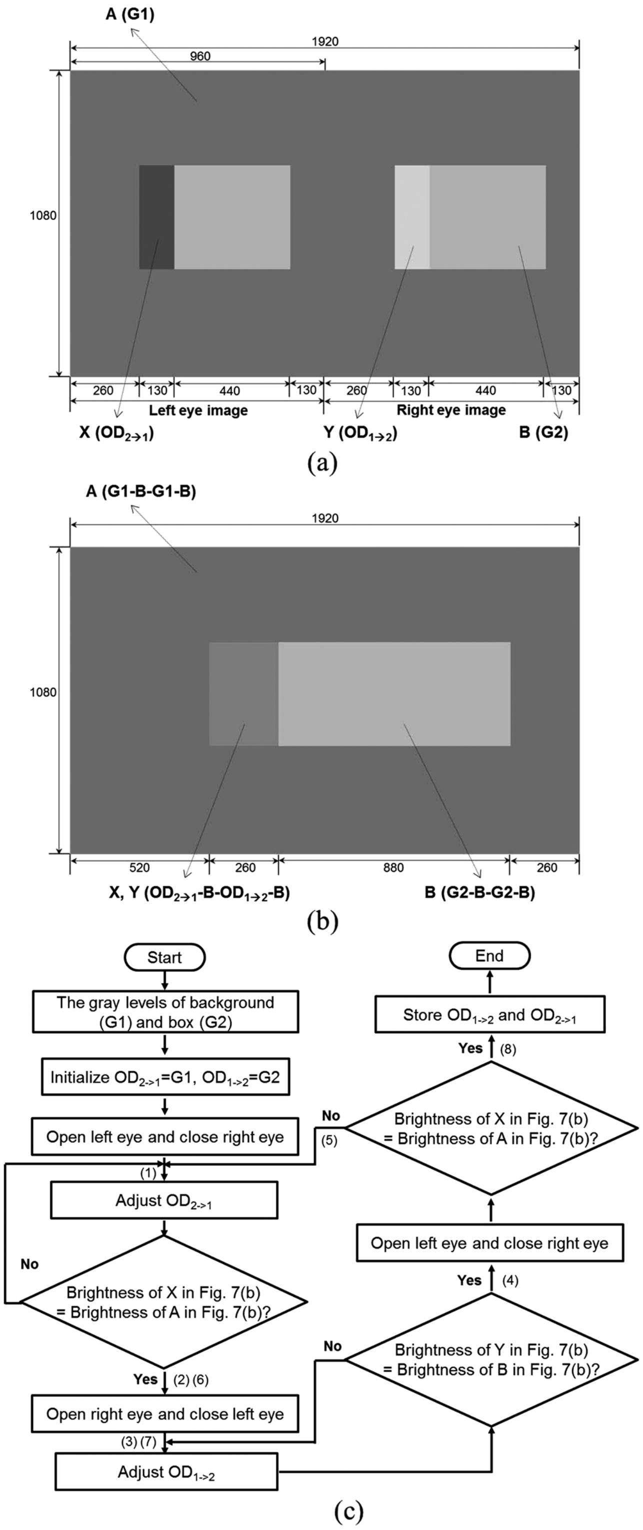

Fig. 9 (a) Software for subjective test. (b) Pattern used in the software. (c) Flowchart of the proposed user-optimization algorithm.

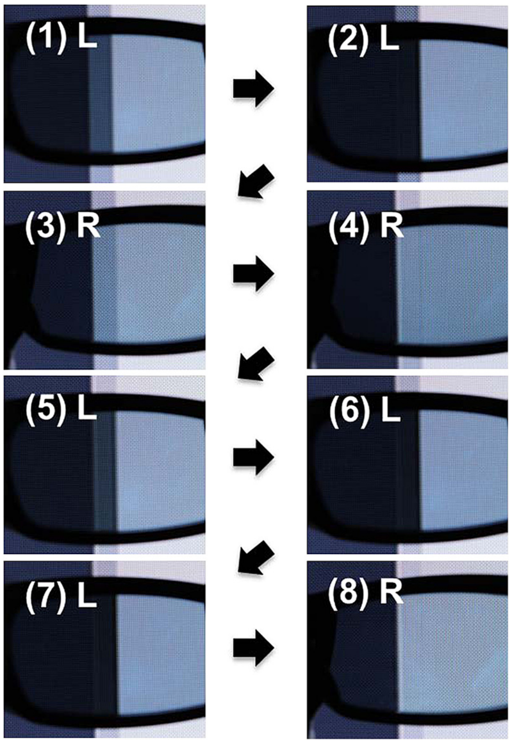

Fig. 10 The actual photographs for each step in Fig. 7(c). *L* and *R* mean the left glass and right one, respectively.

left eye. Then, adjust $OD_{1\to2}$ until brightness of Y in Fig. 9(b) is equal to that of B in Fig. 9(b). When the subject finds the appropriate $OD_{1\to2}$, the brightness of Y is equal to that of B but A and X may have different brightness. It is also due to the fact that a newly adjusted OD value affects the luminance response at the next field. Thus, it is required for the subject to repeat the above steps until the both brightness matches are satisfied. Figure 10 shows the actual photos according to each step denoted by a parenthesized number in Fig. 9(c). At the step (1), the crosstalk phenomenon is observed through the left glass. At the step (2), X/Y region looks the same as the background because an optimum $OD_{2\to1}$ value is found. At the step (3) to (4), the crosstalk seen through the right glass is reduced by applying an optimum $OD_{1\to2}$ value. However, at the step (5), the crosstalk is observed again through the left glass, due to updated $OD_{1\to2}$ at the step (4). At the steps (7) and (8), the brightness of A is the same as that of X/Y region via the left glass, and the brightness of B is the same as that of X/Y region via the right glass, simultaneously. Thus, finally optimized $OD_{2\to1}$ and $OD_{1\to2}$ are found. By the simple iterations, the subject can easily find optimum values for crosstalk minimization.

OD values obtained by using the measuring equipment were compared with the counterparts selected by human eyes. Figure 11 illustrates the comparison results. The symbols connected by black lines show OD values obtained by measurements, and the colored symbols with error bars show OD values obtained by human eyes. The measured OD values in Fig. 11(a) represent the upper right part of the LUT shown in Fig. 7, whereas the OD values in Fig. 11(b) correspond to the lower left part of the LUT. The measured and perceived OD values were very similar as shown in Fig. 11. It means that the proposed crosstalk minimization technology can be simply implemented by the user-friendly selection method with human eyes.

Table 2 shows the user experience report for the user-friendly selection method. It is proved that users can optimize the crosstalk themselves conveniently.

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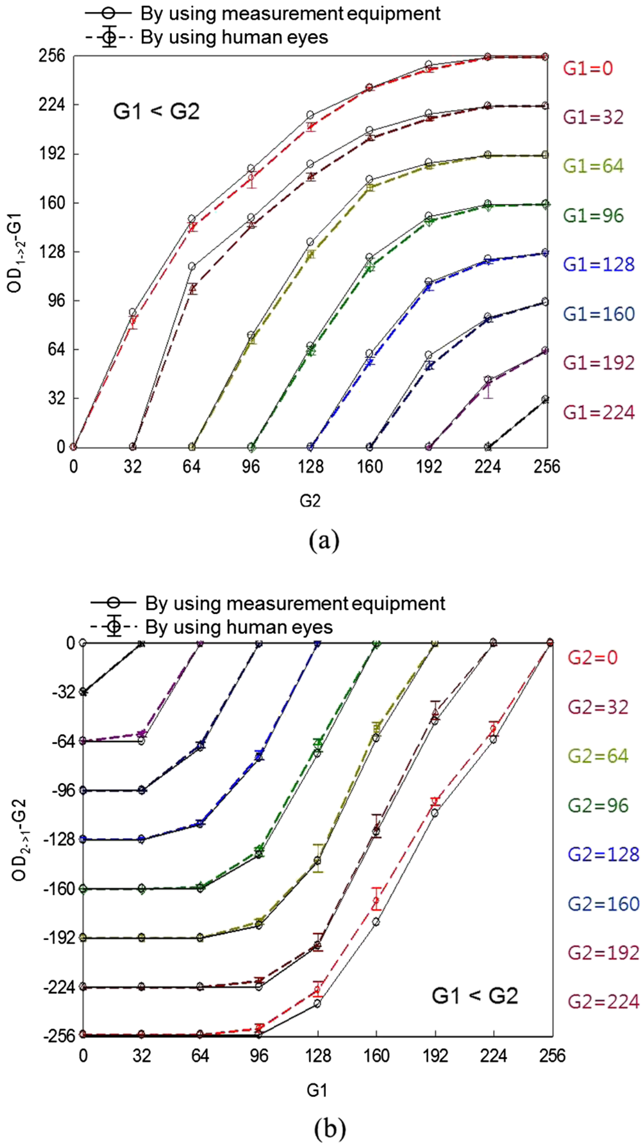

(a)

(b)

Fig. 11 The comparison results of OD values by measurements and visual selections.

Table 2 User experience report for user-friendly selection method.

No	Difficulty (understanding)	Difficulty (operation)	Average time for one transition(s)	Averagerepeat count for one transition
1	Very easy	Very easy	40	2.3
2	Easy	Easy	42	2.1
3	Very easy	Easy	31	2.2
4	Very easy	Normal	40	2.1
5	Very easy	Normal	27	2.3
6	Very easy	Very easy	23	1.9
7	Easy	Easy	64	2.4
8	Very easy	Very easy	45	2.2
9	Very easy	Very easy	53	2.6
10	Very easy	Easy	34	2.4

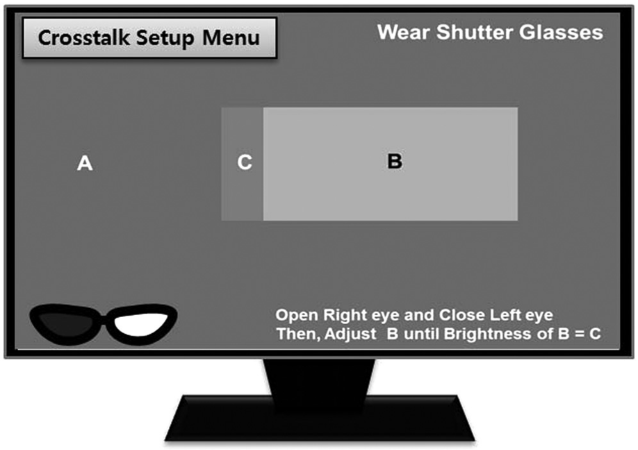

Fig. 12 The conceptual image of optimizing crosstalk reduction by 3-D TV consumers.

Figure 12 illustrates the conceptual image of the setup environment for user-optimized crosstalk minimization. In principle, it is not difficult to include the logic into the TV. The software we presented here can be easily implemented in the TV board because the patterns are so simple to create by using the digital logic. The gray level values of the patterns can be easily adjusted by a firmware. Without the logic in the TV, the users cannot adjust the crosstalk. The users may not need to adjust right after purchasing the TV if the crosstalk is reduced by the TV manufacturer before shipping. Adjusting the crosstalk by the manufacturer results in lowering productivity and increasing costs. In addition, the user must feel the need to reduce the crosstalk after operation for some time because the performance of a product changes with time. We think it is better for the users to make the adjustment rather than for the TV manufacturers to do so. That's why we propose a user-friendly adjustment technology to reduce the crosstalk anytime. If the proposed method is implemented in commercial 3-D TVs, consumers can optimize crosstalk reduction of their 3-D TVs in their home. Therefore, all the consumers who have no knowledge on LCDs can experience the visual comfort, by enhancing their own 3-D TVs by themselves.

5 Conclusion

This paper has proposed a new method to minimize the 3-D crosstalk phenomenon. Furthermore, the additionally proposed user-optimized method enables the crosstalk minimization without any measurement equipment. Therefore, if the proposed method is implemented in 3-D LCD TVs, consumers can easily minimize the crosstalk in their living rooms according to their preferences.

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