FIELD-SEQUENTIAL STEREOSCOPIC VIEWING SYSTEMS USING PASSIVE GLASSES

Philip Bos and Thomas Haven
Tektronix, Inc.
Beaverton, OR

Abstract—At the present time, one of the more feasible approaches for producing 3D video images is to use a single CRT which sequentially displays the left- and right-eye views. This paper discusses the design considerations of such a system that uses a liquid-crystal shutter on the CRT and passive glasses to route the correct images to the eyes of the viewer. A new system with improved performance is described in detail.

I. INTRODUCTION

At the present time one of the more feasible approaches for producing 3D video images is to use a single CRT which sequentially displays the left- and right-eye views at a rate faster than can be perceived by the eye. The incorrect images can be blocked by active glasses using a PLZT material for example.

Recently, liquid-crystal shutters have been used in place of the PLZT devices. The first section of this paper will briefly review the state of the art in active glasses and point out the remaining problems with that approach.

The remainder of this paper focuses on stereoscopic viewing systems that use passive glasses. The systems we have considered use a liquid-crystal shutter placed over the CRT faceplate. The design considerations of such a system, including the issues of LC shutter selections, wavelength dependence of the contrast ratio, and phosphor decay will be discussed.

II. BACKGROUND AND OBJECTIVE

Early 3D video systems using a single CRT and the field-sequential approach used PLZT glasses to block the incorrect images presented to each eye.[1] The PLZT shutters are fast enough to switch during the vertical retrace time of the CRT; however, the interdigitated electrode structure reduces the transmission of these glasses. Also, they can be expensive and require quite high voltages.

Recently, liquid-crystal shutters have been used in active glasses (Table I). Although twisted nematic devices have been used, their switching times are so long that they may only be used in 30-Hz systems where a significant portion of the screen is not used.

Table I. Technologies for active glasses.

Technology	Switching speed	Unusable area of screen: 30-Hz system	60-Hz system
TN	10 msec	50%	N/A
C-N[3]	3 msec	13%	31%
Π-cell[4]	2.5 msec	10%	25%
2-freq. TN[5]	2 msec	7%	15%
Double Π-cell[6]	50 μsec	0	0
SmC*[7]	50 μsec	0	0

The faster switching time of the π-cell[4,8,9] makes it a good alternative for low-cost 30-Hz stereoscopic systems. Although the approximate 2.5-msec switching time of this device is longer than the vertical retrace time, only a small portion of the top or bottom of the screen's image is degraded by the switching speed of the device.

Faster switching shutters have been demonstrated by Phillips[7] and Tektronix.[6,10] The Phillips system uses a ferroelectric liquid crystal and the Tektronix system uses two crossed π-cells. Both systems switch in less than the CRT's vertical retrace time and exhibit good extinction of the unwanted images.

However, even with the performance demonstrated by these improved active glasses there are issues remaining with their use. One is the problem of phosphor decay. Even in the case of many "fast" phosphors, it is several milliseconds before the intensity drops to a low level. This results in an incorrect or ghost image to be viewable especially near the bottom of the screen. (By incorrect or ghost image we mean the low intensity left image that is seen by the right eye and vice-versa.)

To see the nature of the problem, we can consider a system in which each eye view is scanned in 8-msec and a 0.5-msec vertical retrace interval is used. Also, consider that the active glasses switch in an infinitesimal amount of time at the beginning of each field and have perfect extinction. In this case, a spot near the bottom of the image (say 1/2 in. from the bottom of a 19-in. CRT) would be viewed by the correct eye for about 1 msec before the cell would need to switch to open the optical pathway to the other eye. So light emitted from the spot during the first 1 msec after the spot is excited is routed to the correct eye, but light emitted after that due to phosphor persistence (1–9 msec after the spot was excited) will be routed to the incorrect eye.

Notice in Fig. 1 that the integrated light intensity emitted in the interval of time from 1 to 9 msec is seen to be 20% of the amount emitted during the interval form 0 to 1 msec. So the incorrect eye will see a ghost image 1/5 as bright as the correct image.

In addition to this problem, active glasses are either tethered, or heavy if they incorporate "on-board" drivers and a synchronizing link.

Stereoscopic viewing systems using passive glasses have been previously considered. Mash, Crossland, and Morrissy,[2] and Byatt[11] have considered the use of a twisted nematic device on the front of the CRT as a polarization modulator to encode the left and right images. The viewer

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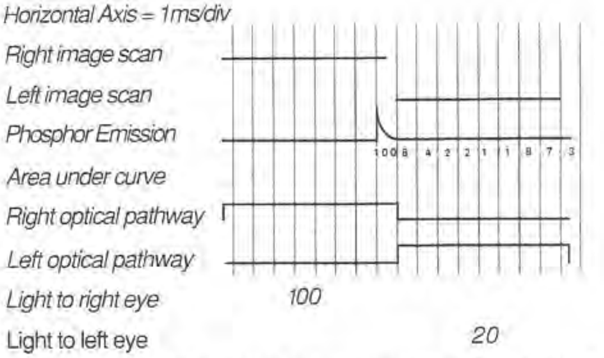

FIG. 1. Illustration of the phsophor decay problem. The shape of the phosphor decay curve is conceptual. The area under the curve in successive milliseconds was measured from a P-22 green phosphor (in arbitrary units).

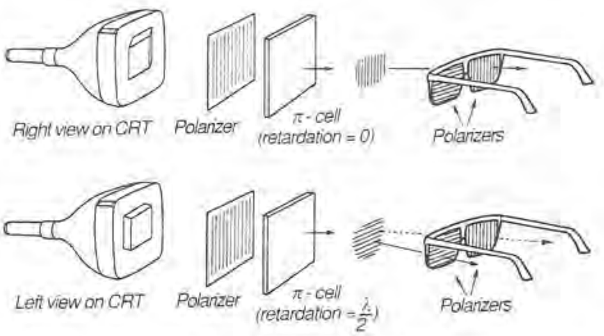

FIG. 2. A "first attempt" stereoscopic viewing system using passive glasses.

then wears polarized glasses and only the correct image (left or right) gets to the eyes.

A problem with this shutter, as with the active glasses, is that a twisted-nematic device switches too slowly for this application. The requirements for the LC polarization modulator here are similar to the requirements for field-sequential color displays. In a previous paper,[12] we discussed two frequency twisted nematic, surface mode, and π-cell devices. The π-cell, with its relatively fast switching time and large angle of view, was shown to be a good choice for field-sequential color displays, so it might be considered in a passive stereoscopic system as shown in Fig. 2.

However, the performance of this "first attempt" system is not satisfactory with regard to the extinction of the undesired images. In the systems using active glasses both views could be extinguished by the zero-retardation state of the LC device, but in this case for one eye the undesired image must be extinguished when the π-cell is in it's half-wave retardation state. This can cause a problem if the shutter is to be used with a color CRT.

Figure 3 shows the transmission through the π-cell and the right lens of Fig. 2, with the CRT replaced by a constant light source. In the operating sytem, the right-eye view could be rastered on the CRT during the time interval V1 and the left eye view during the time interval V2. The LC shutter used here has been tuned to be a half-wave retarder for green light (the cell was 5 μm thick and used a liquid-crystalline material with a birefringence of 0.13), and it can be seen that for 546-nm light the cell blocks light quite well

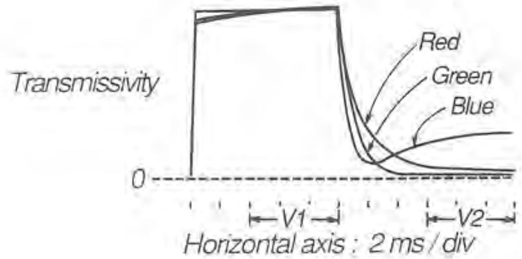

FIG. 3. The light transmission along the optical pathway from the CRT to the right eye of the system in Fig. 2 with the CRT replaced by a constant light source. In an operating system, the right-eye view could be rastered on the CRT during time interval V1, and the left-eye view during time interval V2. The horizontal time scale is 2 msec/div. Blue, 460 nm; green, 546 nm; red, 610 nm.

in the time interval V2. However, by the device's nature as a half-wave retarder, there is imperfect extinction of 460- or 610-nm light. This results in considerable leakage of the blue and red components of the left video image to the right eye.

This system also has the same problem with phosphor decay as the active glasses, and the vertical retrace time is too short for the cell to fully switch states.

The objective of this paper is to describe how these problems can be minimized to allow the design of an acceptable passive stereoscopic system.

III. RESULTS

The wavelength dependence problem shown in Fig. 3 can be understood by considering the transmission expression: $I = I_o \cos^2(\delta'/2)$ where $\delta' = 2\pi \Delta n' d/\lambda$. Here, $\Delta n'$ is the effective birefrigence of the LC cell, d is the cell thickness, and λ is the wavelength of light. It can be seen that the intensity of light transmitted in the cell's half-wave state can only be zero for only one wavelength of light in the visible spectrum.

The light intensity transmitted through crossed polarizers with intervening birefringent materials is $I = I_o \sin(\delta/2)$ where δ is the total phase shift introduced by the birefringent materials (assuming uniaxial materials with their optic axes at 45° to the polarizer's axis).

It can be seen that if $\delta = 0$, the intensity transmitted will be zero for any wavelength. So our approach to solving the wavelength dependence problem has been to design systems in which for each eye the net value of δ is zero in the interval of time light is to be blocked from that eye.

The total phase retardation δ is equal to $2\pi(\Delta nd)_{total}/\lambda$, where $(\Delta nd)_{total}$ is the total distance of one of the orthogonally polarized light components is retarded relative to the other. So equivalent to saying we will require the total phase retardation to be zero, we can require the path length retardation $(\Delta nd)_{total}$ to be zero.

While we have found it possible to do this in several different ways, one of the simpler ways is shown in Fig. 4.

For this system,[13] when the cell is in its zero retardation state the right image is rastered on the CRT. During this time the net retardation of the components of light transmitted to the left eye is seen to be zero since the quarter-

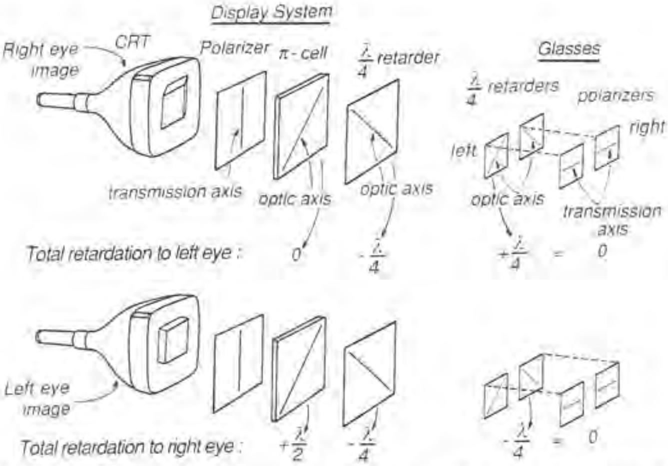

FIG. 4. An example stereoscopic viewing system (one-cell version) in which the net retardation along each eye's optical pathway is zero during the time interval that light is to be extinguished for that eye.

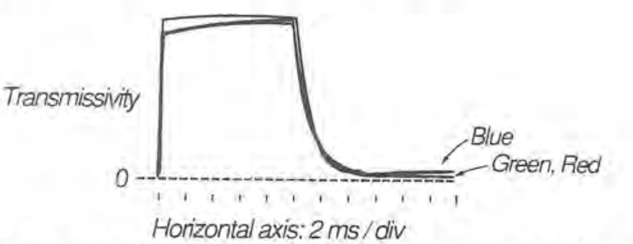

FIG. 5. As Fig. 3, but considering the light transmission to the right eye in the system shown in Fig. 4.

wave retarder on the CRT is crossed with respect to the one on the left lens. As a result all wavelengths of the right image are blocked from the left eye (as was the case with the system of Fig. 2).

The improvement can be seen when the cell is in its half-wave retardation state and the left image is being rastered. During this time the net retardation of the components of light traveling to the right eye is also seen to be zero since the two parallel quarter-wave retarders (on the CRT and in the right lens) are crossed with respect to the LC cell (a half-wave retarder). In this manner, all colors of the left image can be blocked from the right eye.

Figure 5 shows light transmission data taken from the system configuration of Fig. 4 in the same manner that the data of Fig. 3 was taken from the system of Fig. 2. The improved extinction of the blue and red colors during the time interval V2 is apparent.

We have also developed a two-cell system[13] shown in Fig. 6. In this case two crossed π-cells are used that switch between zero and a quarter-wave retardation. When the right eye's image is presented on the CRT the first cell has a high level voltge (around 30 V RMS) applied to it causing it to be in it's zero retardation state, and the second cell is in its quarter-wave retardation state. Because the second cell's retardation can be exactly cancelled by the crossed quarter-wave plate in the left lens of the viewing glasses, little light of any color is transmitted to the left eye.

When the left eye's image is presented on the CRT, the first cell is in its quarter-wave retardation state and the

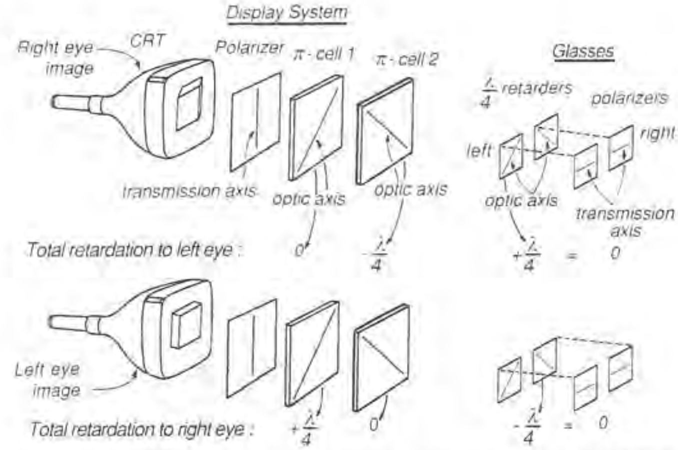

FIG. 6. An example stereoscopic viewing system (two-cell version) in which to net retardation along each eye's optical pathway is zero during the time interval that light is to be extinguished for that eye.

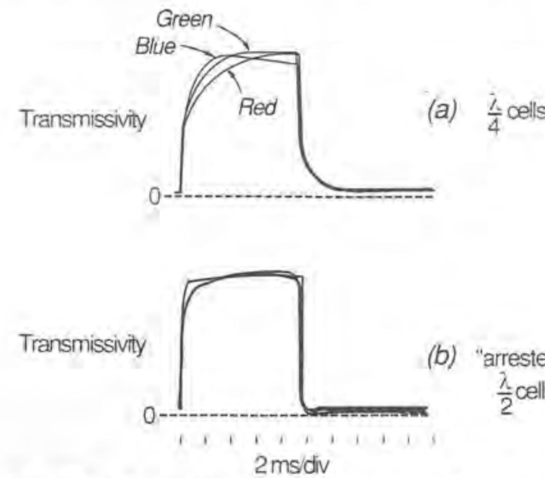

FIG. 7. As Fig. 3, but considering the light transmission to the right eye in the system shown in Fig. 6. (a) Shows data with 5-μm-thick cells using a LC material whose birefringence is 0.07. (b) Shows data with 5-μm-thick cells using a LC material whose birefringence is 0.13.

second in a zero retardation state (voltage applied). During this time the quarter-wave retardation of cell 1 can be cancelled by the crossed quarter-wave plate in the right lens of the viewing glasses causing little light to get to the right eye.

Figure 7(a) shows the light transmission data from this sytem considering the right eye's optical pathway. The CRT has been replaced by a constant light source. The cells used here had the same 5-μm spacing as the cell used in Fig. 4, but here we used a liquid-crystal material with a birefringence of 0.07 so that the cell relaxes to a retardation close to the value of the quarter-wave retarders used in the viewing glasses.

The response speed of the one-cell version or the two-cell version can be increased by making the cells thicker or by increasing the birefringence of the LC material, and then "arresting" their relaxation at an appropriate point.[14] For example, if in the two-cell system we were to use 5-μm cells filled with a LC material that has birefringence of 0.13 they would relax to a half-wave retardation rather than the desired quarter-wave retardation. But we can "arrest" the

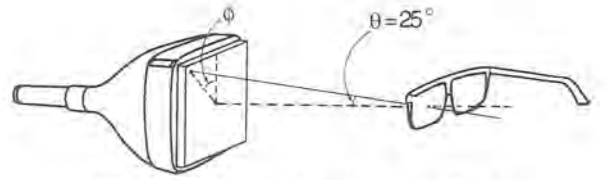

FIG. 8. Definition of angles used in Fig. 9.

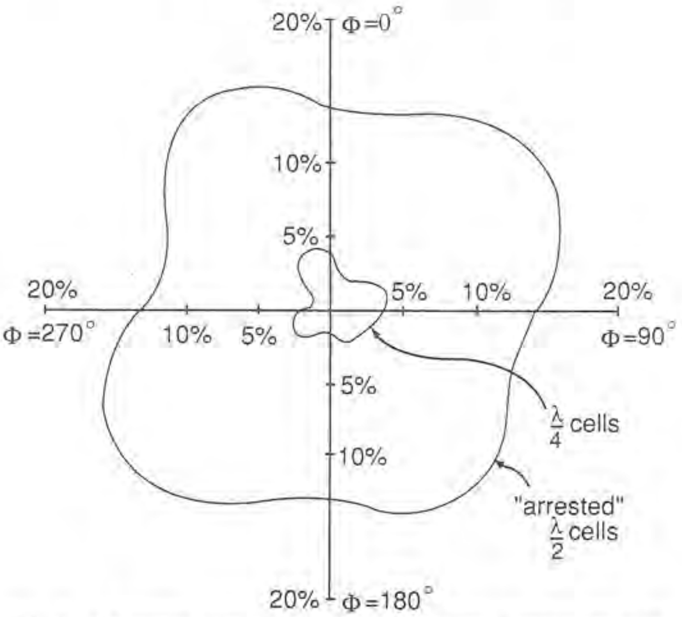

FIG. 9. Calculated light intensity (Ref. 12) for the incorrect image expressed as a percentage of the correct image intensity for the system of Fig. 6. The cases shown are considering the use of the cells referred to in Fig. 7. The director configuration is from Ref. 12 with the electric coherence length adjusted to yield a quarter-wave retardation. The wavelength of light used is 546 nm.

cell's relaxation as it passes through a quarter-wave retardation by applying a small voltage. Because in this case the molecules physically moved less to get the cell retardation to be a quarter-wave than in the case of the lower birefringence cells, the switching speed is faster. Figure 7(b) shows the switching speed of the system of Fig. 6 using 5-μm cells that have a birefringence of 0.13 and have their retardation arrested at a quarter-wave. The penalty for using this speed up technique is a reduced angle of view.

A viewer directly facing a 19-in. CRT at a 18-in. viewing distance will need to look at an approximate 25° angle to the CRT normal to see the screen's corners. Of course, if the viewer moves his head from being directly in front of the CRT this angle becomes greater, so it would not be uncommon for a viewer to view parts of the image at 25° to the screen normal.

Figure 8 defines the angles used in Fig. 9 which shows the computed light intensity that would reach the left eye when the right image is presented. The light intensity is given as a percentage of the "correct" image intensity.

It can be seen that we expect the intensity of the "incorrect" image to be greater when cells are used with a birefringence value greater than needed for devices not using an arresting voltage.

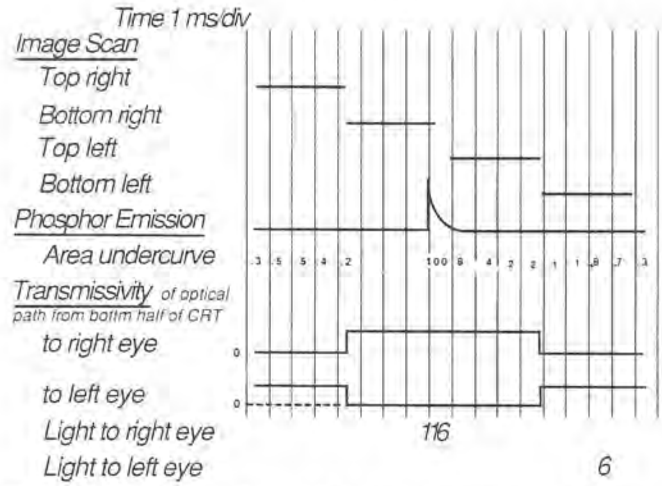

FIG. 10. Illustration of how cell reduces the incorrect or ghost image intensity that is due to phosphor decay.

Table II. The effect of cell sectioning on the incorrect or ghost-image intensity. The ghost-image intensity is expressed as a percentage of the correct image intensity for an image point near the bottom of the screen. Assumes LC cells have a switching time of less than the vertical retrace time of the CRT and provide perfect extinction.

Number of sections	Time for phosphor decay	Ghost image intensity
1	1 msec	20%
2	5 msec	5.3%
3	6.3 msec	4.3%
4	7 msec	3.9%

While either the one- or the two-cell systems can provide good extinction for all wavelengths of light, the phosphor decay problem mentioned in the previous section still exists.

In the case of active glasses there is not much that can be done about this problem, but in the case of passive glasses it is possible to divide the LC cell at the CRT into sections.[9,15] If the cell is split electrically in two sections so that the top and bottom halves can be switched independently, more time is available for phsophor decay. Considering the case of a very-fast-switching shutter for purposes of illustration, Fig. 10 shows that in a two-section cell light will be routed to the correct eye for the additional 4 msec it takes the CRT to raster half of the screen. Table II shows the improvement in the extinction of the ghost image due to phosphor decay for multiple section cells that have a very short switching time.

With the use of sectioned cells the requirement for the cell's switching speed is also less stringent than for the case of active glasses. For example, if the 2.5-msec turn-off time of the system of Fig. 4 is used in place of the very short switching speed assumed in Fig. 10, the amount of light routed to the incorrect eye is 10 units and to the correct eye is 112 units. This results in a ghost image intensity due to phosphor decay of 9.2% of the correct image intensity for the left eye. The much shorter turn-on time of the system should allow the ghost image intensity seen by the right eye to be close to the 5.3% value obtained from Fig. 10.

Table III. Comparison of stereoscopic viewing systems with passive glasses. Perfect extinction of light along the incorrect optical pathways are assumed.

Number of cells	Number of sections	Number of split lines	Left eye ghost image	Right eye ghost image
2	1	0	20%	20%
1	2	1	9.2%	5.3%
2	2	1 pair	5.3%	5.3%
1	4	3	6.0%	3.9%
2	4	3 pair	3.9%	3.9%

Unfortunately the use of sectioned cells has a drawback. With the current technology, the 0.001-in. split lines are wide enough to be visible. Both increasing the number of sections in a cell and going from the one-cell system to the two-cell system increases the number of split lines seen by the viewer.

Table III quantifies the tradeoffs between the ghost image intensity due to phosphor decay and the number of visible split lines. The ghost image intensity for the two-cell version was obtained from Fig. 10 assuming the use of 5-μm cells that used a LC material with a birefringence of 0.13 that were arrested at a quarter-wave retardation.

The ghost image intensity for the one-cell version was arrived at using the phosphor decay curve of Fig. 10 but the cell turn off characteristic of Fig. 5. Because the one-cell version switches on very quickly, only the left eye's ghost image intensity is decreased when going from the one- to the two-cell version.

We have found that the pairing effect of having one split line behind another in the two-cell system to be objectionable, so when considering Table III it is appropriate to consider "1 pair" to be worse than "2".

Which of the options listed in the Table is best depends to some extent on the type of images presented and on user requirements. However, for many applications, the one-cell version with two sections provides a good compromise between the number of split lines and ghost image intensity.

In conclusion, it should be noted that there are more detailed factors beyond those related to basic system design that need to be taken into account when considering the ghost-image intensity. For example, we have not taken into account the ghost-image intensity that results from the leakage of light along the incorrect optical pathway. The causes of imperfect extinction (non-zero retardation of the π-cell in the field applied state, imperfect matching of the retardations of the passive retarders and π-cells, the dynamic nature of the off-state of the π-cell, the wavelength dependence of the birefringence of the passive retarders, and the viewing angle dependence of the retardation of the passive retarders and the π-cells) will be discussed in a later paper.

IV. CONCLUSION

Designing a "passive" stereoscopic viewing system where each eye's optical path has a net zero retardation during the interval of time light is to be blocked for that eye, permits good extinction of all colors. Furthermore, the additional problem associated with phosphor decay can be controlled by the use of a multisection liquid-crystal cell.

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