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J. L. Fergason[a]; A. L. Berman[a]
[a] Optical Shields Ltd, Menlo Park, California, U.S.A.

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A push/pull surface-mode liquid-crystal shutter: technology and applications

by J. L. FERGASON and A. L. BERMAN
Optical Shields Ltd, 1390 Willow Road, Menlo Park, California 94025, U.S.A.

The construction, operating principles and electro-optics of a surface-mode liquid-crystal shutter are reviewed. The shutter is composed of two glass plates, the inner surfaces of which are coated with a transparent electrically conductive layer. The substrates are treated to induce parallel director alignment. Polarizers are placed on the front and back of the cell oriented at right angles to each other and at 45° to the director. In the surface mode of operation a sustaining voltage is applied to the cell. This causes the director in the centre of the cell always to be oriented parallel to the electric field. The amplitude of the applied voltage determines the thickness of the surface layer—the layer in which the director orientation varies from parallel to the surface to parallel to the electric field. Light travelling through the cell will encounter retardation only in the surface layers. Hence the voltage controls the retardation of the cell, and by that means the polarization state of the light travelling through the cell. By adjusting the voltage so that the retardation is changed from 0λ to $\frac{1}{2}\lambda$ the shutter can switch from open to closed. It is possible to construct a faster-switching shutter. This so-called push/pull shutter is composed of three elements in optical series. The first two are surface-mode cells oriented such that their directors are perpendicular. The third element is a quarter-wave plate with its axes parallel to the directors. The three elements are placed between orthogonal polarizers, with the directors oriented at 45° to the polarizers axes. The closed state of the shutter is obtained by placing one shutter in the high-voltage 0λ state and the other in the low-voltage $\frac{1}{4}\lambda$ state. The open state of the shutter is obtained by switching the voltage levels applied to the two cells. The operating principles and the electro-optics of this device are discussed in detail.

1. Introduction

Many types of liquid-crystal devices (such as those that utilize the familiar twisted nematic effect) change states in a time no faster than tens of milliseconds. Such devices are therefore too slow for use as components in some high-speed optical systems. The factor limiting the speed of these devices is the requirement that all of the directors within the cell must reorient to accomplish an optical change. Here we discuss a means by which a device can be constructed having a much faster switching speed, of the order of a few hundred microseconds. The key to obtaining high speed is to limit the volume of the sample within the liquid-crystal cell that has to move physically in order to manifest an optical change. The name given to this type of component is a 'surface-mode device' (SMD). The SMD is particularly useful because it can be fabricated using conventional twisted nematic manufacturing techniques. Furthermore, two SMDs and several passive components can be put into optical series to form an even faster device called a push/pull SMD. The construction, operating principles and electro-optics of both single- and dual-cell SMDs are discussed in this paper. Also discussed will be the use of a push/pull SMD as a fast optical shutter in a cathode-ray-tube based three-dimensional display system.

2. Discussion

2.1. *The single-cell SMD configuration*

Consider first the construction of a single-cell SMD as illustrated in figure 1 [1]. The shutter is composed of two glass plates, the inner surfaces of which are coated with a transparent electrically conductive layer. The conductor is in turn coated with a rubbed alignment layer to induce parallel director alignment. The space between the substrates is filled with the nematic liquid crystal. Polarizers are placed on the front and the back of the cell, oriented at right angles to each other and at 45° to the director. The construction is similar to that of the twisted nematic display. Therefore the techniques that are reuqired to fabricate SMDs are well known and should present little difficulty to liquid-crystal-display manufacturers. The exact details of the shutters used in our experiments are being kept confidential at the request of the manufacturer.

The operation of the device is explained with reference to figure 2. In figure 2 (*a*) the director arrangement of the cell is shown when there is no voltage applied. Figure 2 (*b*) illustrates the director configuration when a low voltage is applied to the cell. Notice that most of the directors align parallel to the electric field. This layer of material is called the bulk. Note also that the directors at the surface are fixed to the surface and do not reorient. Consequently there is a thin region between the surface and the bulk in which the directors adopt intermediate orientations. This region is called the surface layer. Since the liquid crystal is birefringent, the surface layer will introduce retardation to polarized light travelling through the layer. The amount of retardation depends on the thickness of the surface layer and hence on the applied voltage. When a low voltage is applied such that the resulting retardation is $\frac{1}{2}\lambda$ polarized light travelling through the cell will be rotated by 90° and transmitted through the analyser. Figure 2 (*c*) illustrates the state of the cell when a high voltage is applied. The thickness of the surface layer has decreased to only those directors directly in contact with the surface. The retardation of the layer is reduced to only a

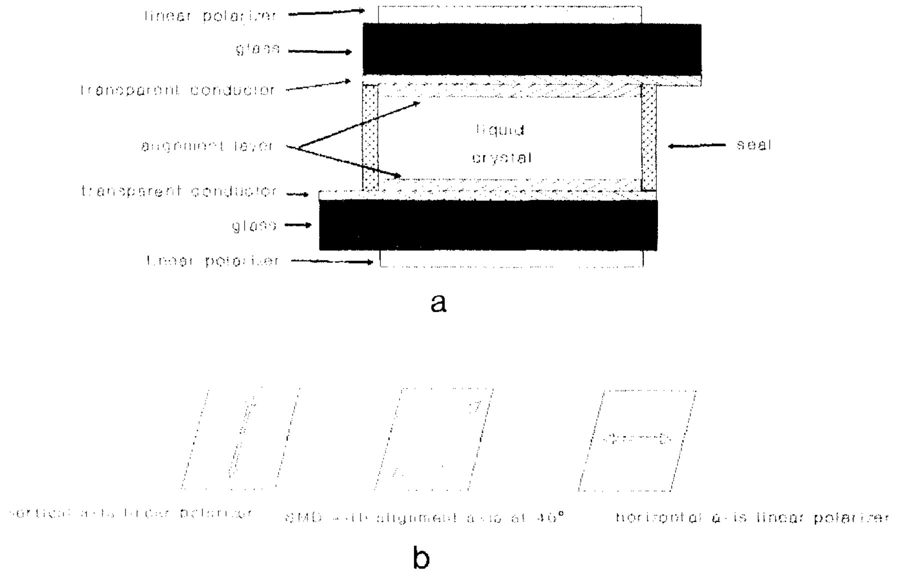


Figure 1. Construction of a single-cell SMD: (*a*) side view; (*b*) orientation of components.

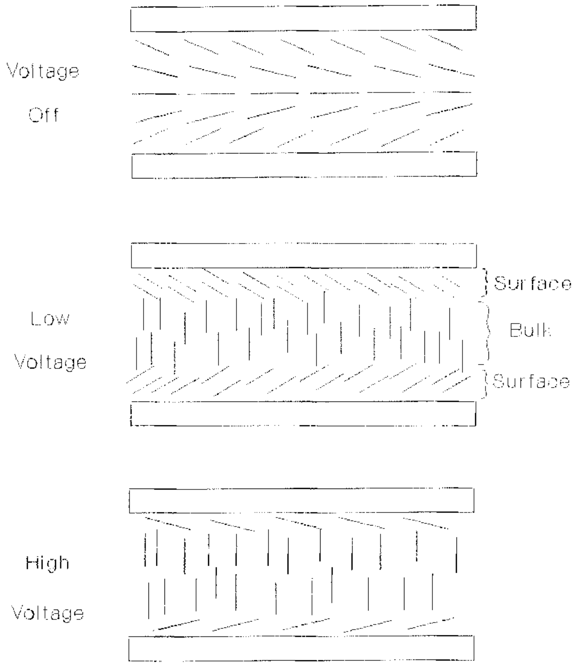
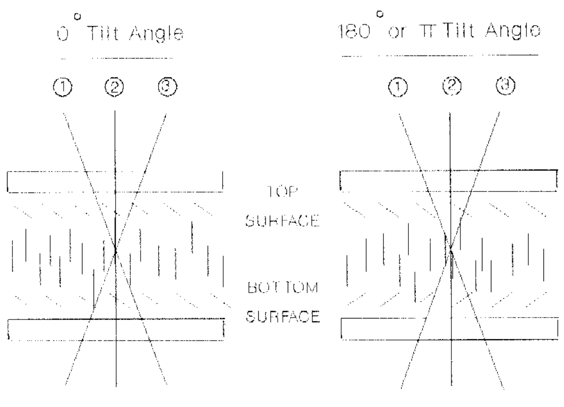


Figure 2. Side view of SMD illustrating director orientation in operating modes.

residual amount, about $\frac{1}{64}\lambda$. Hence the light travelling through the cell in the high-voltage state will not have its polarization altered and will therefore be absorbed by the analyser. The shutter is operated between the high-voltage closed state and the low-voltage open state.

The speed of the SMD is a consequence of several factors. In switching from the open state to the closed state the voltage is increased. The resulting electric field exerts an enormous torque on the directors. It is, however, only those directors in the surface layer that are available to reorient. The active layers are thin and therefore respond very fast. To switch from the closed to the open state, the voltage is lowered. The dominant force on the surface-layer directors becomes the reorienting torque caused by the surface alignment. This torque is transmitted by elastic forces between the directors, and, over the distance of the surface layer, is very strong. hence the reorientation time is short. Note, however, that the magnitudes of the various forces that act to reorient the directors are such that the time to switch to the closed state is of the order of a few hundred microseconds while the time to switch to the open state is of the order of a millisecond. In addition there is a slight but significant dependence of the switching time on wavelength. This is due to the dispersion of the liquid crystal. In general the shutter will switch fastest in the blue, slower in green and slowest in red.

In the closed state the shutter is found to exhibit a variation in optical density as a function of viewing direction. There are two components that contribute to this angular variation. The first is the thickness of the bulk layer—the thinner this liquid-crystal layer, the wider the good-viewing cone. The second factor relates to the tilt angle of the directors at the surface layers [2]. This is explained with reference to figure 3. The surface alignment technique utilized in the SMD induces a small tilt bias



(a) (b)

Retardation	Ray 1	Ray 2	Ray 3	Retardation	Ray 1	Ray 2	Ray 3
Top surface	$> \frac{1}{4}\lambda$	$\frac{1}{4}\lambda$	$< \frac{1}{4}\lambda$	Top surface	$> \frac{1}{4}\lambda$	$\frac{1}{4}\lambda$	$< \frac{1}{4}\lambda$
Bottom surface	$> \frac{1}{4}\lambda$	$\frac{1}{4}\lambda$	$< \frac{1}{4}\lambda$	Bottom surface	$< \frac{1}{4}\lambda$	$\frac{1}{4}\lambda$	$> \frac{1}{4}\lambda$
Total	$> \frac{1}{2}\lambda$	$\frac{1}{2}\lambda$	$< \frac{1}{2}\lambda$	Total	$\frac{1}{2}\lambda$	$\frac{1}{2}\lambda$	$\frac{1}{2}\lambda$

Figure 3. Explanation of π-alignment to obtain a wide good-viewing angle.

to the director at the surfaces. There are two ways in which the tilt on the top surface can be oriented with respect to the tilt on the bottom surface. In figure 3 (*a*) the tilt bias at the top surface is in the same direction as the bottom surface. This is called 0° alignment. Only light rays travelling along the cell normal will encounter exactly $\frac{1}{2}\lambda$ retardation and therefore be blocked by the analyser. Rays that enter the cell obliquely will experience more or less than $\frac{1}{2}\lambda$ retardation. These rays will not be completely absorbed by the analyser. The result is that the good-viewing cone of the 0° aligned SMD is very restricted. The other possible arrangement is shown in figure 3 (*b*). The tilt on the top surface is in the opposite direction to the tilt on the bottom surface. Opposite tilt is equivalent to a 180° rotation of the director and leads to the naming of this type of director arrangement as π-alignment. In a π-aligned SMD a decrease (increase) in retardation at the top surface is compensated by an increase (decrease) in retardation at the bottom surface. This effect assures that all light rays travelling through the SMD will experience $\frac{1}{2}\lambda$ retardation and will be blocked by the analyser. The good-viewing cone of the π-aligned SMD is much wider than an equivalent 0° aligned SMD.

There are some negative features of the performance of the single-cell shutter. These include the fact that the switching time for the shutter is asymmetric, being much slower in the closed-to-open direction. Furthermore, the darkness of the closed state is reduced by two effects. The first is a result of the residual birefringence. If the retardation of the closed cell were exactly zero then the polarization state of the transmitted light would be unchanged and completely absorbed by the analyser. Since the retardation is not exactly zero, there is a slight alteration in the polarization state of the transmitted light. The light becomes elliptically polarized, leaks through the analyser and degrades the darkness of the closed state. The second effect is a result of the waveform that drives the cell. This waveform has not yet been discussed, but is illustrated in figure 5, where it is seen to be a 2 kHz square wave modulated at

120 Hz. The cell is fast enough that in the closed state it can partially respond to the carrier wave. The resulting 4 kHz variation in the retardation shows up as a periodic reduction in the darkness of the closed state. Hence the average darkness of the closed state is reduced.

A further characteristic of the SMD shutter is that the darkness of the closed state is a function of wavelength. This is due to the dispersion of the liquid crystal and the consequent fact that the retardation of the cell can be exactly $\frac{1}{2}\lambda$ for only one wavelength. Only this wavelength will be rotated by precisely 90° and so be completely absorbed by the analyser. All other wavelengths will be elliptically polarized and so will leak slightly through the analyser.

2.2. *The push/pull SMD configuration*

All of the negative attributes of the single-cell SMD can be addressed by utilizing the so-called push/pull configuration [3]. The components of the push/pull SMD are illustrated in figure 4 and are as follows. The first element in the optical series is a vertical linear polarizer. Next are two SMD cells oriented with their director axes orthogonal and at 45° to the vertical. This is followed by a quarter-wave plate with its fast axis oriented at $+45°$. The last element is a horizontal linear polarizer.

The operation of the push/pull SMD is explained with reference to figure 5. The waveforms used to energize the cells are illustrated at the top of the figure. They are composed of a 2 kHz square-wave carrier modulated at the frequency that the shutter is to switch. In this example the modulation is shown as 120 Hz. The relationship between the drive signals to the two cells is such that when SMD 1 is in the high-voltage state SMD 2 is in the low-voltage state, and vice versa. (Note that this type of drive scheme is used in a device called a push/pull amplifier. It is from the amplifier that the name of this type of shutter is derived.) The high voltage is chosen to be in the range 24–40 V peak and drives the SMD into the nominally zero-retardation state. The low voltage is in the range 0–8 V peak and drives the SMD into the $\frac{1}{4}\lambda$ retardation state. Since SMD 1 is oriented at $-45°$, the retardation it introduces is negative, while SMD 2, oriented at $+45°$, introduces positive retardation. During the time frame

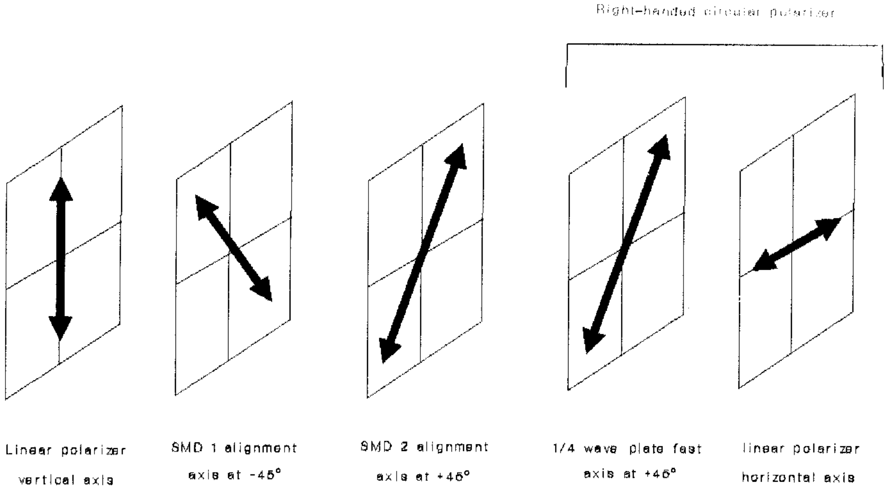
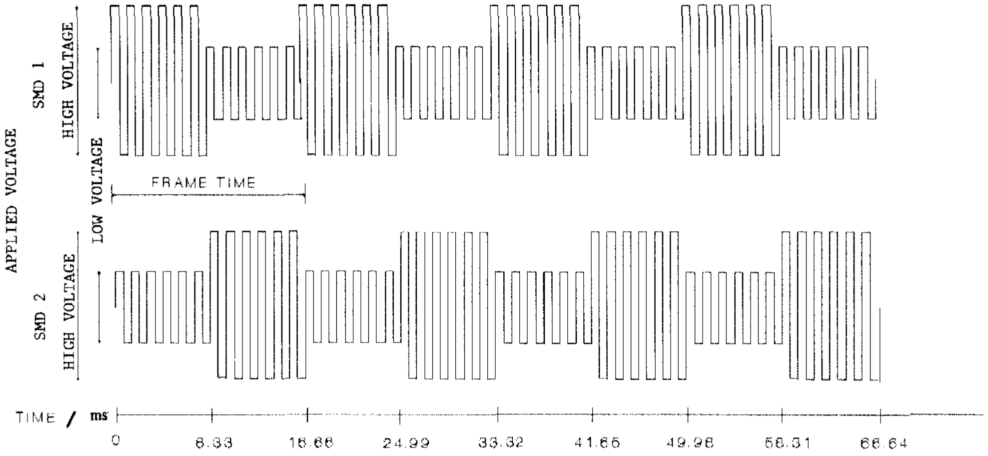


Figure 4. Configuration of a push/pull SMD.



Retardation of SMD 1	0	$+\frac{1}{4}\lambda$	0	$+\frac{1}{4}\lambda$	0	$+\frac{1}{4}\lambda$	0	$+\frac{1}{4}\lambda$	0
Retardation of SMD 2	$-\frac{1}{4}\lambda$	0	$-\frac{1}{4}\lambda$	0	$-\frac{1}{4}\lambda$	0	$-\frac{1}{4}\lambda$	0	$-\frac{1}{4}\lambda$
Total retardation	$-\frac{1}{4}\lambda$	$+\frac{1}{4}\lambda$	$-\frac{1}{4}\lambda$	$+\frac{1}{4}\lambda$	$-\frac{1}{4}\lambda$	$+\frac{1}{4}\lambda$	$-\frac{1}{4}\lambda$	$+\frac{1}{4}\lambda$	$-\frac{1}{4}\lambda$
Light output	LHCP	RHCP	LHCP	RHCP	LHCP	RHCP	LHCP	RHCP	LHCP

Figure 5. Drive scheme for a push/pull SMD shutter.

when SMD 1 is in the high-voltage state the net retardation of the system is as follows: 0λ from SMD 1, $-\frac{1}{4}\lambda$ from SMD 2 and $+\frac{1}{4}\lambda$ from the quarter-wave plate. The sum is 0λ. Hence light that enters through the vertical polarizer will not experience a change in its polarization state while traversing the devices. The light will therefore be blocked by the horizontal analyser. The shutter is closed. During the time frame when SMD 1 is in the low-voltage state the net retardation of the system is as follows: $+\frac{1}{4}\lambda$ from SMD 1, 0λ from SMD 2 and $+\frac{1}{4}\lambda$ from the $+\frac{1}{4}\lambda$ wave plate. The sum is $\frac{1}{2}\lambda$. The incoming vertically polarized light will experience a rotation of 90° and be transmitted through the horizontal analyser. The shutter is open.

Let us consider the push/pull SMD in the light of the problems that were pointed out with regard to the single-cell SMD shutter. Whenever the shutter switches, whether from open to closed or from closed to open, one SMD cell is always switching to the high-voltage state and one is always switching to the low-voltage state. For this reason the push/pull switching times are symmetric. In addition, the switching times of the push/pull SMD are faster than that of a single-cell SMD. This is because less retardation must be switched in a push/pull SMD ($\frac{1}{4}\lambda$) than in the single-cell SMD ($\frac{1}{2}\lambda$). In fact, to switch half the retardation requires one quarter of the time.

The closed state of the push/pull shutter is darker than the closed state of the single-cell shutter. This is because the two problems discussed previously are solved. In the push/pull shutter the positive residual retardation of SMD 1 can be compensated by a slight adjustment to the low voltage and hence the negative retardation of SMD 2. In this way the total retardation can be made exactly $-\frac{1}{4}\lambda$. In this case the light is transmitted without change in polarization, and is therefore blocked by the analyser. The converse of this statement is also true. Secondly, the positive retardation ripple that occurs in SMD 1 will be exactly compensated by the negative retardation ripple in SMD 2. This serves to increase the average darkness of the closed state of the shutter.

There is one aspect of the push/pull approach that is a disadvantage compared with the single-cell SMD. The push/pull shutter, having two cells, has twice the bulk-layer thickness of the equivalent single-cell SMD. It was noted earlier that the thicker the bulk layer, the smaller is the good-viewing cone. The viewing cone of a push/pull shutter can be widened by utilizing a liquid crystal with a lower birefringence. This approach does, however, involve a trade-off inasmuch as lowering the birefringence also reduces the switching speed. We recall though that the push/pull SMD is inherently four times faster than the single-cell SMD, so there is significant speed against which to trade. In practice the good-viewing cone of a push/pull shutter can be made equal to that of a single-cell SMD. A push/pull shutter designed in this way will still have good speed as well as the other advantages discussed previously, plus one more. The lower the birefringence of the liquid crystal, the greater is the allowed variation in the cell gap before there is an objectionable change in the optical performance of the shutter. This has practical consequences. A large allowed variation in the cell gap should translate into a cell that is easier and less expensive to manufacture. Hence a cell used in push/pull shutter can be less expensive than a cell used in single-cell shutter.

3. A cathode-ray-tube- (CRT-) based stereoscopic video system

Here we discuss the use of a push/pull shutter in a field-sequential, CRT-based, three-dimensional display system [4]. The three-dimensional effect is accomplished through the use of binocular disparity. That is, the viewer is presented with two views of the outside world, corresponding to a right-eye and a left-eye perspective. The function of the shutter is to assure that the right-eye perspective views are seen only by the right eye, and vice versa. The system for accomplishing this is illustrated in figure 6. The key is a push/pull shutter that is distributed between the CRT and the viewer. A linear polarizer with a vertical axis and two SMDs are mounted on the CRT. A $\frac{1}{4}\lambda$ wave plate and a linear polarizer with a horizontal axis are worn by the viewer in the form of glasses. The components in the right lens of the glasses are oriented so as to form a right-handed circular polarizer, and in the left lens then form a left hand circular polarizer. The right- and left-eye perspective views are presented on the CRT sequentially. The first frame displayed on the CRT is a right-eye perspective. The voltages to the SMDs are set so that the light leaving the CRT is right-hand circularly polarized. This view is transmitted through the right-hand circular polarizer of the right lens and blocked by the left-handed circular polarizer of the left lens. During the next frame a left-eye perspective is displayed on the CRT. The voltages to the SMDs are adjusted so that the view is left-hand circularly polarized. This view is transmitted by the left-handed circular polarizer of the left lens but blocked by the right-handed circular polarizer of the right lens. The left and right views are alternated at 120 Hz. This presents 60 frames per second to each eye. Since this is above the flicker fusion frequency, a steady image is perceived. The shutter is switched during the vertical retrace of the CRT. A particular advantage of using a push/pull shutter in this application as opposed to a single-cell shutter is that the contrast ratio and the transmission are the same to both eyes. Furthermore, since the

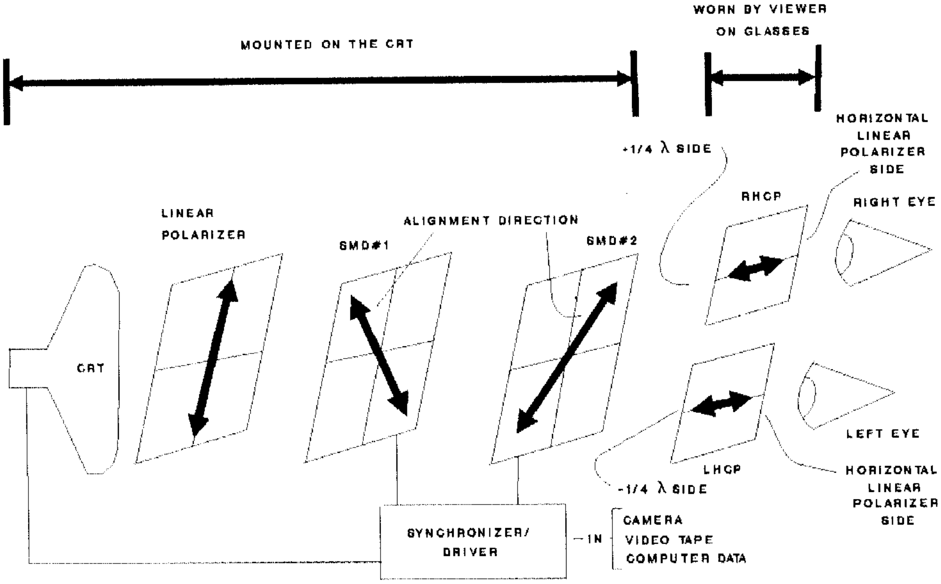


Figure 6. A CRT-based stereoscopic video system utilizing a push/pull SMD as the shutter element.

light leaving the CRT is circularly polarized, the orientation of the analyser does not affect the contrast ratio of transmission. That is to say, the shutter characteristics will not change when the viewer's head is tipped.

4. Conclusion

The construction and the principles of operation of a fast electro-optic shutter have been described. The speed of the surface-mode liquid-crystals device is a result of reducing to a minimum the amount of liquid crystal within the cell that has to reorient to produce an optical change. A wide good-viewing cone is obtained through the use of π-alignment. A device that responds even faster and that has symmetrical turn on and off times was constructed from two SMDs. This push/pull SMD also had a darker closed state because the ripple and the residual birefringence of the first cell were compensated by that of the second. Experiments to measure the contrast, transmission and speed are currently underway and will be the subject of a later paper. The SMD shutters can be manufactured using the same procedures used to fabricate twisted nematic displays and are currently commercially available in sizes up to 12 in. × 16 in. (Stereographics Corporation, San Raphael, California, and Tektronix Corporation, Beaverton, Oregon.) A frame-sequential stereoscopic three-dimensional video system has been described that utilizes a distributed push/pull shutter. The viewer wears circular polarizers as glasses. The advantages of this approach are that the contrast ratio and the transmission are the same for each eye and were not effected by head-tipping. In summary, a high-quality artefact-free three-dimensional image is obtained from this system.

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