Electron-Beam Addressed Liquid-Crystal Light Valve

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***Abstract*–A new light valve is described. The device is a cathode-ray tube (CRT) that incorporates a liquid-crystal cell as the electron-beam target. This light valve uses simple "slide projector" optics and has demonstrated initial (nonoptimized) performance of 512 × 512 line resolution and >50:1 contrast ratio.**

Introduction

PROJECTION displays that use interactive light valve technology generally fall into two categories: 1) displays in which the light-modulation medium is coupled by means of a photoconductor to the addressing system, and 2) displays in which the light modulator is directly addressed—usually by electron beam or laser.

Liquid-crystal light modulators have been laser addressed [1] and photoconductor coupled [2], [3] to a CRT or other light source. Laser-addressed systems, while having very high resolution [4] are storage devices that may require several seconds to fill the screen [5] and that use generally complex optical systems for both addressing and projection. The photoconductor-coupled devices, in addition to the requirement for addressing optics, either use multilayer construction [2] to isolate the projection and addressing light or have severe constraints on the wavelength of the addressing/projection light [3].

The idea of an electron-beam addressed liquid crystal is conceptually attractive, since all problems with photoconductors, dielectric mirrors, and light-blocking layers could be eliminated. In addition, the device could be made sufficiently fast for real-time operation. Early work by Hansen and Schneeberger [6] demonstrated the feasibility of switching a cholesteric liquid crystal across a dielectric membrane by electron-beam modulation. This produced a color shift in the written regions.

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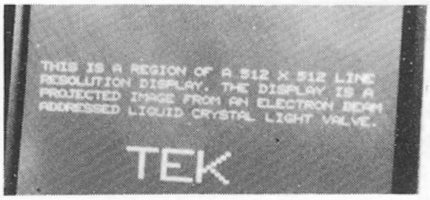

Fig. 1. Projected image from light valve (screen size = 56-in diagonal).

The potential uniformity problems in a refreshed display caused by the transition from the Grandjean structure to the light scattering (stable) focal-conic texture that has been observed in cholesteric cells [7] could be avoided by use of nematic liquid crystal in twist-cell configuration. A projected image from an electron-beam driven nematic liquid-crystal cell is shown in Fig. 1.

Device Description

The LC CRT data reported in this paper were taken on an experimental CRT that was fabricated from readily available in-house components. No attempt was made to optimize the electron-optics system. The electron gun uses electrostatic deflection and focus. The nominal spot size for this gun is 0.003 in at 50-V drive.

In its simplest configuration (Fig. 2), the light valve functions as an interactive slide projector—the electron beam writes information on the "slide." The light valve consists of a writing gun, the flood guns, and the target, which is a liquid-crystal cell. In this device, the target electrode is a thin sheet of dielectric material. The backplate electrode is an indium tin oxide (ITO) coated faceplate. These electrodes are aligned and configured to define a 90° twist cell. The electrodes are spaced approximately 10 μm apart and are filled with nematic liquid crystal (Fig. 3).

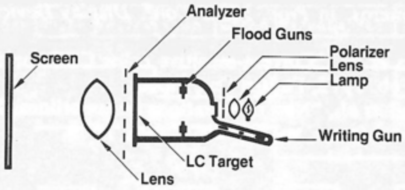

Fig. 2. LCCRT light valve projection system.

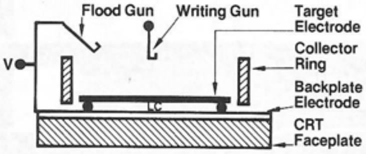

Fig. 3. Light valve schematic view.

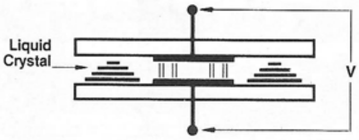

Fig. 4. Twisted nematic liquid-crystal cell.

Cell Fabrication

Because the cell is part of the CRT internal environment, the integrity of the cell must be maintained at high vacuum. Also, any cell spacing or uniformity changes under vacuum must be minimal.

The cells in the devices reported were fabricated from stretched dielectric membrane (mica, polyimide, and glass micro sheet were evaluated) as the target electrode and used ITO coated float glass as the backplate electrode. The surface alignment was SiO, which was evaporated at 5° from the plate surface. These electrodes were oriented to form a 90° twist configuration and were sealed at the perimeter with epoxy. The cells were filled under vacuum with thoroughly degassed liquid crystal.

Theory of Operation

In a twisted nematic liquid-crystal cell, the liquid-crystal molecules are ordered such that plane-polarized light passing through the cell is rotated 90°. When sufficient voltage is applied to the cell, the molecular axes of the LC molecules orient themselves parallel to the applied electric field. Polarized light, then passes through the cell unchanged in the "switched" region (Fig. 4).

We may consider the e-beam-addressed liquid-crystal light valve or liquid-crystal CRT (LCCRT) to be roughly equivalent to the cell shown in Fig. 4 with the electron beam supplying the switching voltage. In fact, an early attempt to construct a beam-addressed LC was fabricated from a matrix of pin's in a glass substrate [8]. This early light valve exhibited a variety of problems including low resolution and pin-to-pin crosstalk.

The device shown in Fig. 3 has an unstructured target electrode, in which the driving voltage is supplied by the electron beam striking the dielectric target with sufficient energy to cause the surface to charge positive toward some collector potential (Fig. 5). With the collector ring held at some positive

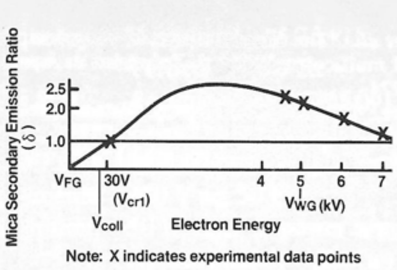

Fig. 5. Secondary emission curve for mica target.

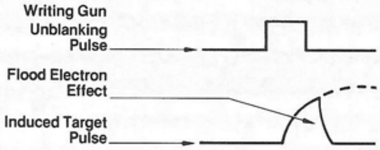

Fig. 6. Transient voltage of written spot on target.

potential (V_{coll}), which is lower than the writing threshold for the target, the effective potential of the dielectric target will be below the first crossover voltage (V_{cr1}) and no storage[1] of the trace will take place. Thus it is possible to refresh the display.

Since the flood electrons maintain the target surface at the backplate potential (Fig. 3), no field appears across the cell except in written areas. The unwritten regions are maintained at or near the flood-gun cathode potential (V_{fg}) by flood electrons. These low-energy flood electrons also oppose the writing effect of the writing gun to rapidly discharge the written regions (where $V_{targ} < V_{cr1}$). Therefore, if we assume that all writing is performed at flood-electron energies less than V_{cr1}, the voltage pulse at the target surface is as shown (Fig. 6).

Switching Voltage

We can model the liquid-crystal cell as a capacitor (representing the target electrode) in series with a variable capacitor (representing the liquid crystal). The variable capacitance is due to the dielectric anisotropy of the liquid crystal. The effect on the operation of the cell is considerable since, if we assume a nonequilibrium condition under writing-gun bombardment (i.e., the surface does not charge to a fixed potential), then the voltage across the LC cell at any written element is given by

$$V = \frac{1}{C} \int^{t} I_B \, dt$$

To illustrate this situation, we may assume the following conditions in order to calculate the writing-beam current required to deposit sufficient charge (neglecting any effect of secondary emission) to switch the cell. The threshold voltage represents the first point of cell "turn-on," and the saturation voltage (V_{sat}) is the minimum voltage across the cell for maximum contrast.

These twist-cell potentials have corresponding dielectric

[1]Although bistable storage has been demonstrated by the author in a manner similar to that proposed by Chang *et al.* [9] it is necessary to locate a fine-pitch collector mesh close to the target in order to achieve acceptable stored-trace resolution. This mesh reduces light transmission and degrades contrast in a transmissive device.

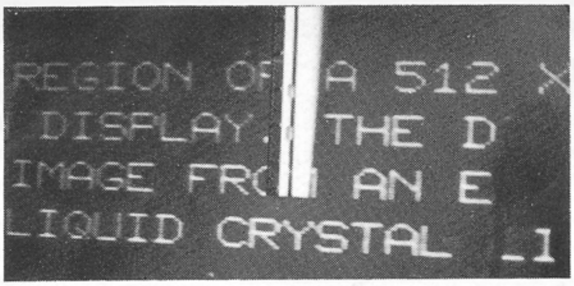

Fig. 7. Close-up of projected image shows resolution obtained. (Dash markings on ruler are inches.)

constants ($\epsilon_\perp$, $\epsilon_{/\!/}$). For the particular liquid crystal used in these cells $\epsilon_\perp = 5$ and $\epsilon_{/\!/} = 12$.

Let

I_B = writing beam current

$t = 6.4 \times 10^{-8}$ s (512 X 512 line raster at 60 Hz)

$$C = \frac{\epsilon A}{d}$$

$A = 9.8 \times 10^{-5}\ \mathrm{cm}^2$ (at trace width $(TW) = 4.4$ mil)

(LC spacing $(d) = 10\ \mu$m).

For a charge deposition to deliver a threshold voltage of 1 V across the liquid crystal at the LC threshold, a beam current of $I_B = (VC/t)$ would be required. $\epsilon_\perp = 5$, then

$$I_B = \frac{(1\ \mathrm{V})(4.34 \times 10^{-14}\ \mathrm{F})}{6.4 \times 10^{-8}\ \mathrm{s}} = 0.7 \times 10^{-6}\ \mathrm{A}.$$

However, for a charge corresponding to $V_{sat} = 10$ V, then: $(\epsilon_{/\!/} = 12)$

$$I_B = \frac{10\ \mathrm{V}(1.04 \times 10^{-13}\ \mathrm{F})}{6.4 \times 10^{-8}\ \mathrm{s}} = 16.2 \times 10^{-6}\ \mathrm{A}.$$

Resolution

Device resolution seems to be limited by the sum of the electron-beam diameter and the charge spreading in the target/liquid-crystal sandwich. This expectation has been supported by experimental data on the devices we tested. The current target-resolution limit (as measured by visual observation of a shrinking raster) is approximately 225 lines/in. However, at this time, the largest contribution to spot size is the electron-beam diameter (0.003 in), which could be reduced significantly. Fig. 7 shows a photo of a projected image on a front-projection screen, which represents an approximate 20 X magnification of the image as written on the light valve.

Contrast Ratio

If we define contrast ratio as equal to

$$\frac{\text{transmission in "ON" state}}{\text{transmission in "OFF" state}}$$

it is clear that, in order to maximize the contrast, it is necessary to minimize T_{off}. This off-state transmission in a twist cell depends primarily on the birefringence of the liquid crystal and on the thickness of the cell. If the cell is sufficiently thick

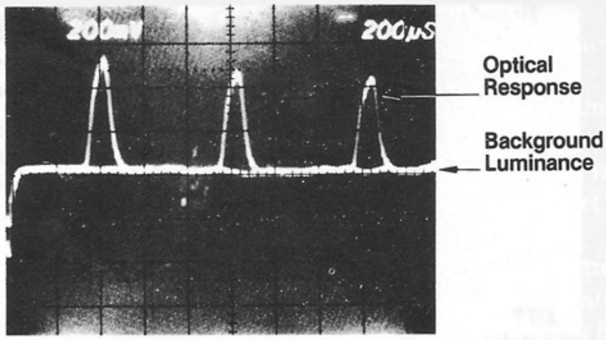

Fig. 8. Oscilloscope traces obtained when LCCRT raster is projected onto a Reticon diode array reflect 59:1 contrast ratio.

or if $(\Delta nd/\lambda) = K$, where λ is the wavelength of transmitted light [10] and K is an integer multiple of π such that $(\Delta nd/\lambda)$ corresponds to the zeros of $\sin K\pi$, the off-state transmission will be minimum and the contrast will be as good as the extinction ratio for the polarizers ($>$50:1).

Fig. 8 shows the contrast of a projected raster on a Reticon diode array. The 300-W slide projector lamp (filtered to $\lambda \approx 0.6\ \mu$m) delivers 58.6 fL on a 5 X gain rear-projection screen, with 1.0-fL background luminance measured with a TEKTRONIX J6523 1° Luminance Probe. In this light-valve cell, the liquid crystal birefringence $(\Delta n) = 0.18$ with cell spacing $(d) = 10\ \mu$m.

Writing Speed

Since the writing speed of the device is limited by the time required to deposit a charge that is sufficient to bring the cell voltage to V_{sat} we can apply the expression

$$\text{Area } WS = \frac{I_B(\delta - 1)}{\frac{C}{A}\Delta V}$$

where

I_B is the beam current

C/A is the capacitance per unit area of the liquid crystal

ΔV is the switching voltage

δ is the secondary electron emission ratio ($\delta > 1$).

(For the light-valve CRT under consideration:)

$$I_B = 14.7 \times 10^{-6}\ \mathrm{A}$$

$$C/A = \frac{1.04 \times 10^{-13}\ \mathrm{F}}{9.8 \times 10^{-5}\ \mathrm{cm}^2}$$

$$\Delta V = V_{sat} = 10\ \mathrm{V}$$

$$\delta_{(5\,\mathrm{kV})} = 2.3 \text{ (Fig. 5)}.$$

Then

$$WS = \frac{(14.7 \times 10^{-6}\ \mathrm{A})(1.3)}{(1.06 \times 10^{-9}\ \mathrm{F/cm}^2)(10\ \mathrm{V})}$$

$$WS = 1.8\ \mathrm{cm}^2/\mathrm{ms}.$$

For a trace width of 4.4 mil, this writing speed is roughly equivalent to 500 X 600 lines at a 50-Hz refresh rate.

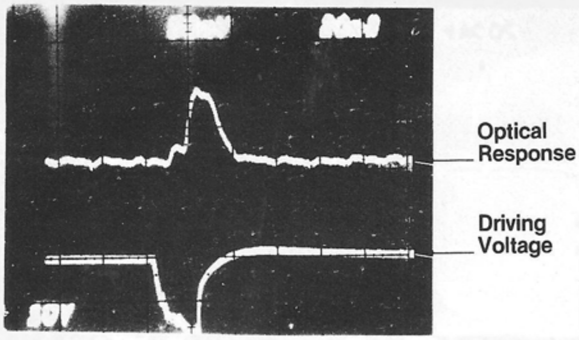

Fig. 9. Oscillograph of LCCRT transient response (20 ms/div).

Switching Speed

As shown in Fig. 9, the cell switches on in approximately 5 ms when a driving pulse of sufficient magnitude to carry the cell to V_{sat} is applied. The optical response lags the driving voltage and decays in about 20 ms. At TV rates with animation, this decay time could cause some image "smear" but would be adequate and indeed desirable for graphic displays where some image persistance is advantageous.

Conclusion

This electron-beam addressed liquid-crystal light valve operating in a transmission-projection mode offers performance suitable for many display applications.

Performance Summary

Switching Speed . . . . Approximately 25 ms.
Contrast Ratio . . . . 59:1.
Resolution . . . . 225 lines/in (target).
Writing Speed . . . . 1.8 cm^2/ms.

Acknowledgment

The author thanks P. Bos for his consultation on liquid-crystal systems.

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