Modulation depth characteristics of a liquid crystal television spatial light modulator

Glenn D. Boreman and Edward R. Raudenbush

The performance of a commercially available liquid crystal TV display was characterized in terms of its modulation depth. Measurements of screen transmittance and modulation depth, as a function of signal level, showed that the primary limitations of the device as a spatial light modulator were due to the nature of the video scan format and the display drive electronics. The resolution of the device, as measured by the modulation transfer function, is limited more by the physical pixel spacing than by pixel crosstalk. The optical flatness of the screen was characterized interferometrically, both with and without polarizers, to show the improvement in wavefront quality obtained by replacing the original polarizers.

I. Introduction

Liquid crystal arrays originally intended for small-format TV display applications have recently become popular as spatial light modulators.[1–7] These video-addressed liquid crystal devices can cost up to 2 orders of magnitude less than competing technologies and are thus attractive for experimental work in optical processing, particularly at an initial demonstration stage.

Since the arrays and their drive electronics were not designed for use as spatial light modulators there are performance limitations in areas such as resolution, contrast, dynamic range, and optical flatness. This paper concentrates on the array performance in terms of modulation depth. The scanned nature of the video data format and the screen drive electronics both tend to decrease the dynamic modulation which the device can produce. A statically measured contrast ratio yields an optimistic estimate of the performance actually obtained for most applications.

II. Principles of Operation of the Display

The mechanism of operation of this modulator is the twisted nematic effect.[8] A liquid crystal cell is configured between two parallel polarizers. Within the cell, a liquid crystal material resides in a narrow gap between two pieces of glass. A transparent electrode grid allows voltage to be applied across any individual pixel. The inside surfaces of the glass are treated so that the liquid crystals orient helically from one side of the cell to the other. Light polarized along the director of that helix at the cell surface follows the director of the liquid crystal and emerges from the exit face of the cell rotated through 90°. This is the state of the cell with no voltage applied and corresponds to a minimum transmission state, because the input light is blocked by the output polarizer.

In the device under test, the director of the liquid crystal was along the diagonal direction of the screen. Light polarized along either diagonal remained polarized on propagation through the cell and exhibited a rotation of the polarization state. Input light of other polarization states exhibited elliptical polarization at the output face with a resulting loss of contrast.

As the voltage across a particular cell increases from zero, the helix structure is gradually destroyed by an alignment of the liquid crystal molecules along the direction of the applied E field. The transmittance of the cell rises from the minimum in a fairly steep transition. The cell eventually proceeds to a state where polarized input light is not appreciably rotated by the liquid crystal molecules. The structure thus has its maximum transmittance for a large applied field.

The liquid crystal array tested had 140 pixels horizontally and 120 pixels vertically. Individual pixels were located at the intersection of the transparent drive electrodes for the rows and columns. The active area of each pixel was 0.33 × 0.33 mm with a 0.01-mm transparent border around each.

Glenn Boreman is with University of Central Florida, Electrical Engineering Department, Center for Research in Electro-Optics & Lasers, Orlando, Florida 32816, and E. R. Raudenbush is with Rome Air Development Center, Griffiss AFB, New York 13441.

Received 22 September 1987.
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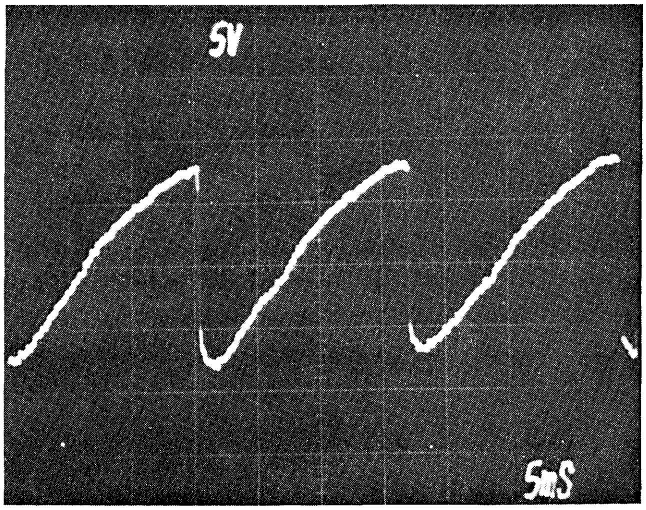

Fig. 1. Light transmitted by a single pixel as a function of time. Increasing transmission is in the downward direction.

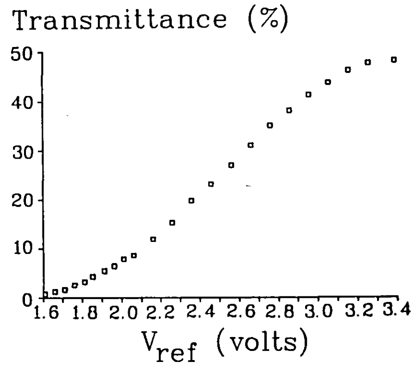

Fig. 2. Transmittance of a single pixel of the display as a function of V_{ref}. The measurement was made for a uniform bright screen of video data with variation in the brightness setting producing the range of V_{ref}. Input light was plane polarized and aligned for maximum transmittance.

The fact that the device was addressed by a video signal had an impact on the performance characteristics. The analog waveform is sampled at times corresponding to the spatial location of the pixels, and the display is written one line at a time with all elements of a particular line written simultaneously.

The analog video signal is sampled rather coarsely by the liquid crystal matrix, resulting in aliasing effects for images containing high spatial frequencies. The entire video image is displayed without overscan on the 140 × 120 format.

The sampled value of the signal information is impressed on an individual pixel by pulsing the corresponding electrode, making that pixel location transmissive in proportion to the value of the video signal at that instant in time. The scanned nature of a video display means that the pixels were refreshed at a rate of 60 Hz.

The electrodes addressing each cell are pulsed once per video frame time. The pulses have a very short duration compared to the characteristic relaxation time of the liquid crystal cell. There was almost a complete decay of the pixel response by the onset of the next pulse. This affected the maximum contrast obtainable from the device, since a pixel has its maximum transmission only over some fraction of each frame time.

III. Measurement Methods and Apparatus

To quantify the screen performance, the screen transmittance was measured in a variety of signal conditions. The measurements were made with a plane-polarized He–Ne laser ($\lambda = 0.6328\ \mu$m). The plane of polarization of the laser was aligned so as to have maximum transmittance through the input polarizer. The laser was focused with a 10-power microscope objective, resulting in a spot size smaller than an individual pixel. The location of the focused spot was adjustable. A large-area calibrated photodetector was placed on the opposite side of the array. Either the time-averaged flux could be recorded, or the actual waveform could be displayed on an oscilloscope.

The video waveforms needed for the array characterization were produced by microcomputer-based image processor system. The signal set corresponded to different uniform screen brightnesses and a collection of square waves of various spatial frequencies.

The transmittance of the screen depends on both the value of the video waveform which drives it and the setting of the brightness control. A convenient reference point for the actual voltage impressed on the screen (for uniform video inputs) is provided by terminal TP 835 on the printed circuit board.[9] The voltage at this point will be denoted as V_{ref} when the video signal input corresponds to a uniform field of maximum brightness. Once V_{ref} is specified, the effect of different video signals can be investigated with the screen bias as a parameter.

IV. Performance Characteristics

A. Temporal Response

Figure 1 shows the amount of light transmitted by a single pixel as a function of time. Increasing transmission is in the downward direction. The pulse shape is due to the scanned nature of the array's video format. The duty cycle of the modulator is not 100%; therefore, the transmittance of the device is smaller than would be indicated from polarizer losses alone. The transmittance of the pixel is not at its maximum value throughout the entire cycle, and for the usual applications the transmittance averaged over several refresh cycles is the parameter of interest rather than the peak transmittance of the element.

B. Screen Transmittance vs V_{ref}

Figure 2 shows the measured screen transmittance vs V_{ref}. For a properly polarized input beam, the maximum value of transmittance τ_{max} was 47%. This is primarily due to the duty cycle of the driving pulses seen in last section. The minimum value of transmittance τ_{min} was 0.5% due to the finite extinction of the device's original polarizers.

The curve of Fig. 2 establishes the operating characteristic of the display as a function of the brightness control setting. The static contrast ratio (τ_{max}/τ_{min}) was nearly 100:1 for this device. Its dynamic performance as a spatial light modulator is less than the static contrast ratio. The waveform which drives the screen can produce only a limited range of voltages along the operating characteristic, centered around an average level set by the brightness control. For a single brightness setting the range of video inputs from black to white is less than the full dynamic range of the screen.

C. Modulation Depth vs V_{ref}

How does the limited excursion range referred to in the last section affect the device's dynamic performance? The pertinent figure of merit[10] for a spatial light modulator is the modulation depth M:

$$M = \frac{\tau_{max} - \tau_{min}}{\tau_{max} + \tau_{min}}.$$

To have a large value for M, the minimum transmittance must be very near zero. That is, the device must be effective at blocking light in the off state while retaining as high a transmittance as possible in the on state.

Figure 3 shows the modulation depth vs V_{ref}. The curve was measured by recording the screen transmittance for a uniform maximum video signal τ_{max} and for a uniform minimum video signal τ_{min} as a function of V_{ref}. The effect of the limited excursion mentioned in the last section may be seen, since the modulation depth peaks at a relatively small value of V_{ref}. The curve of Fig. 2 suggests that the device should be capable of producing values of M very close to 1. In dynamic (video-driven) conditions, the device uses only a limited range of the operating characteristic for a given brightness setting. The maximum value of M which can be attained (0.68) is achieved for a small value of V_{ref} and hence at a small value of screen transmittance.

For $V_{ref} = 1.75$ V, the smallest τ_{min} value of 0.5% can still be obtained. For larger values of V_{ref}, the range of excursion on the operating characteristic does not include that lowest value for τ_{min}, and a decrease in M is observed even though the overall transmittance of the device is higher.

D. Modulation Transfer Function

The modulation transfer function (MTF) is a measure of the usable device resolution, comparing the magnitude of the modulation depth at a given spatial frequency with the magnitude of the low-frequency modulation depth. MTF is strictly defined for sinusoidal input signals. However, we will consider a square-wave MTF, because high frequency sinusoidal inputs tend to be displayed as staircase functions on the screen. This is due to the coarseness of the sampling lattice of the array. Figure 4 shows the square-wave MTF for the device under test. The brightness control was set so that V_{ref} was 1.75 V for a uniform bright screen. This was the condition which yielded the maximum zero-frequency modulation depth (0.68) in Fig. 3. The MTF was measured by recording τ_{max} and τ_{min} for a single pixel, while the display was being driven by square waves of constant modulation depth and varying spatial frequency.

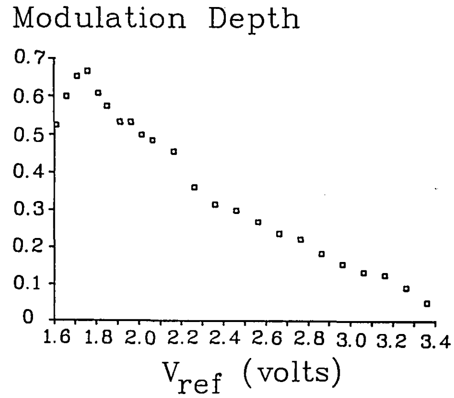

Fig. 3. Modulation depth as a function of V_{ref}.

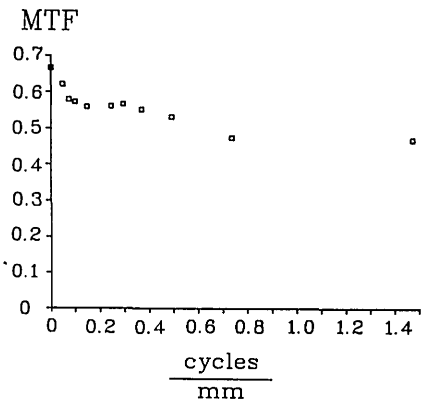

Fig. 4. Square-wave modulation transfer function vs screen spatial frequency in cycles/mm.

Figure 4 shows that the array had a fairly flat transfer function out to its spatial Nyquist frequency of 1.5 cycles/mm. At that frequency, the MTF of the array was ~75% of its value at zero spatial frequency. The resolution of the device is thus limited more by the relatively coarse pixel spacing than by effects such as crosstalk between pixels.

E. Optical Flatness

The transmitted wavefront quality of the modulator is crucial for uses in coherent optical processing. The original plastic-film polarizers supplied with the device are of poor optical quality in this regard, and an improvement in the coherent performance of the device may be obtained by replacing the polarizers[2] or by using a liquid gate.[6] We compare the transmitted wavefront quality of the device, both with and without the original polarizers. Figure 5 shows a double-pass interferogram ($\lambda = 0.6328\ \mu$m) of the original device, and Fig. 6 shows an interferogram of the device with

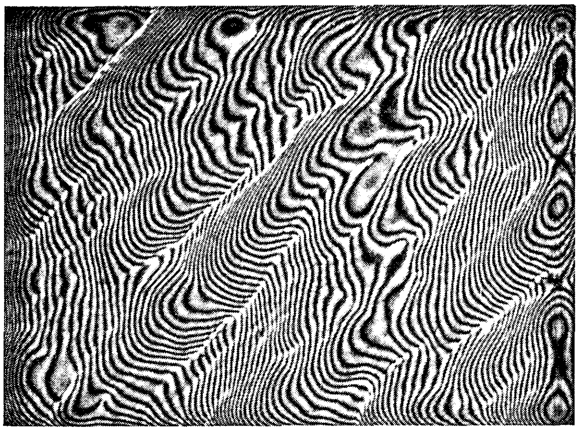

Fig. 5. Double-pass interferogram (λ = 0.6328 μm) of the screen with the original polarizers.

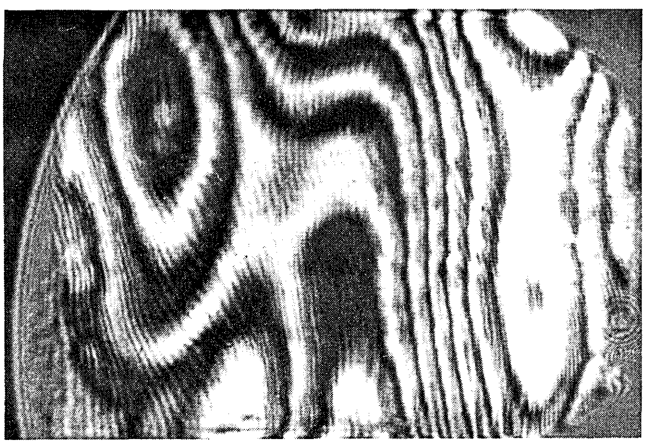

Fig. 6. Double-pass interferogram (λ = 0.6328 μm) of the screen with the polarizers removed.

the polarizers removed. In Fig. 6, the departure from flatness is still several waves, but the device in the modified configuration has markedly improved wavefront quality.

V. Conclusions

The liquid crystal TV spatial light modulator characterized in this paper is usable in optical processing applications. The major drawbacks of the device are its limited modulation depth and its limited resolution. The modulation depth is affected by two factors. The video format of the array necessitates a time-multiplexed arrangement for addressing the pixels. This makes the maximum transmittance of a pixel occur over only some fraction of the frame time. The other limitation to modulation depth is that the video drive circuitry of the array does not allow the entire operating characteristic of the device to be covered. The full range was available with the brightness control, which effectively set the midpoint for the excursions along the operating characteristic. However, under dynamic operation, the range of video levels from black to maximum brightness was insufficient to cover the full transmittance range of the modulator at any one brightness setting.

Desirable modifications to the drive electronics would hold the pixel values over the full frame time and would allow the normal range of video to cover the entire transmittance range. These modifications would make the liquid crystal array itself more useful for optical processing. Removal of the original polarizers resulted in a dramatic improvement in the transmitted wavefront quality of the device.

The spatial Nyquist frequency of 1.5 cycles/mm is more than an order of magnitude below that of specialized spatial light modulators, so this device has a very limited space–bandwidth product. The MTF of the device was limited more by the pixel spacing than by crosstalk effects.

This work was supported by the Engineering and Industrial Experiment Station and the Center for Research in Electro-Optics and Lasers, both of the University of Central Florida.

References

1. D. Casasent and S. Xia, "Phase Correction of Light Modulators," Opt. Lett. **11**, 398 (1986).
2. D. Gregory, "Real-time Pattern Recognition Using a Modified Liquid Crystal Television in a Coherent Optical Correlator," Appl. Opt. **25**, 467 (1986).
3. H. Liu, J. Davis, and R. Lilly, "Optical-Data-Processing Properties of a Liquid-Crystal Television Spatial Light Modulator," Opt. Lett. **10**, 635 (1985).
4. F. Mok, J. Diep, H. Liu, and D. Psaltis, "Real-Time Computer-Generated Hologram by Means of a Liquid-Crystal Television Spatial Light Modulator," Opt. Lett. **11**, 748 (1986).
5. A. Tai, "Low-Cost LCD Spatial Light Modulator with High Optical Quality," Appl. Opt. **25**, 1380 (1986).
6. M. Young, "Low-Cost LCD Video Display for Optical Processing," Appl. Opt. **25**, 1024 (1986).
7. M. Young and M. Weppner, "Hybrid Computer-Optical Processing with Inexpensive Liquid Crystal Television," Proc. Soc. Photo-Opt. Instrum. Eng. **700**, 146 (1986).
8. L. M. Blinov, *Electro-Optical and Magneto-Optical Properties of Liquid Crystals* (Wiley, New York, 1983), pp. 125–130.
9. *Technical Service Manual, Model 16-151* (Tandy Corp., Ft. Worth, TX, 1983).
10. D. Casasent, "Performance Evaluation of Spatial Light Modulators," Appl. Opt. **18**, 2445 (1979).