Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713926090

Photoaddressed liquid crystal devices

D. Armitage[a]; J. I. Thackara[a]; W. D. Eades[a]
[a] Research and Development Division, Lockheed Missiles and Space Company, Inc., Palo Alto, California, U.S.A.

To cite this Article Armitage, D. , Thackara, J. I. and Eades, W. D.(1989) 'Photoaddressed liquid crystal devices', Liquid Crystals, 5: 5, 1389 — 1396

To link to this Article: DOI: 10.1080/02678298908027776

URL: http://dx.doi.org/10.1080/02678298908027776

Liquid Crystals, 1989, Vol. 5, No. 5, 1389–1396

Photoaddressed liquid crystal devices

by D. ARMITAGE, J. I. THACKARA and W. D. EADES
Lockheed Missiles and Space Company, Inc., Research and Development
Division, Palo Alto, California 94304, U.S.A.

Photoaddressed liquid crystal spatial light modulator devices are described and discussed. The initial experimental behaviour of a GaAs photoaddressed ferroelectric liquid crystal spatial light modulator is reported and compared with a similar nematic liquid crystal device.

1. Introduction

In photoaddressed devices the electric field activating the liquid crystal is controlled by a photoaddressing element. Figures 1 and 2 illustrate a reflective readout device, where the photoaddressing element and liquid crystal are separated by a dielectric mirror. The entire input image can be written simultaneously in a photoaddressed device, rather than the electronic matrix line-by-line addressing. Optical isolation of the readout light from the photoactivated element allows high brightness readout, with consequent optical input–output gain. Devices of this general form are called light valves, or spatial light modulators, in deference to the two dimensional modulating structure. The option of incoherent to coherent light conversion is inherent to the structure.

The spatial light modulator is an essential component in optical processing systems, facilitating the propagation and manipulation of information in the optical domain. Two dimensional information flow at the input and output planes is the critical advantage of optical systems. The spatial light modulator characteristics are specified by resolution, aperture, sensitivity, frame speed, contrast and optical quality. Optical processing systems, in general, demand much higher specifications than imaging requirements [1, 2].

The first photoaddressed devices used photoconductors such as cadmium sulphide, which are slow in response and severely restrict the frame rate [3]. The search for a better photoconductor appears to be concentrating on the amorphous silicon–hydrogen alloys [4, 5]. The photoconductor frame-rate limitation has prompted the development of monocrystalline photoreceptors [6–12]. In addition to speed, the single crystal photoreceptor has higher photoefficiency. The high carrier mobility in monocrystalline semiconductors implies a depletion-mode photoreceptor structure.

Ohmic or injecting contacts must be avoided in depletion-mode operation. Schottky barrier and p–n junction connections have been used [8, 11, 13]. The photoreceptor input write side can also be capacitively coupled as shown in figures 2 and 3, thereby eliminating the contact problem [6, 7, 10, 12]. Capacitive coupling simplifies the photoreceptor design, and the absence of barrier losses improves the writing efficiency. Moreover, bipolar operation is possible, which is always an advantage with liquid crystals, because of ionic current flow and electrochemical effects.

The resolution of the spatial light modulator is compromised by transverse motion of the photogenerated charge in the semiconductor. Charge-confinement structures

0267-8292/89 $3.00

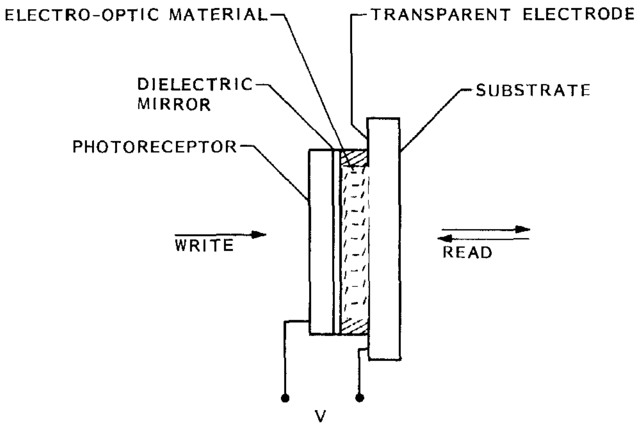

Figure 1. Reflective readout photoaddressed spatial light modulator.

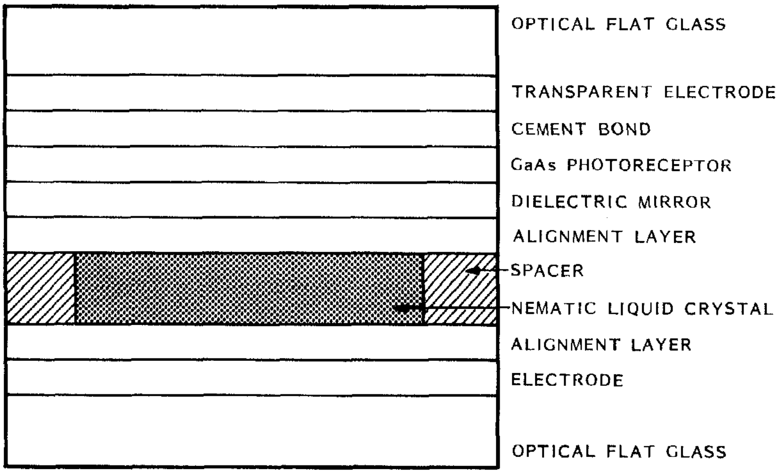

Figure 2. General structure of a photoaddressed liquid crystal spatial light modulator.

can be fabricated from p–n junction or Schottky barriers [8, 9, 11]. Alternatively, dielectric barriers that are not polarity sensitive can be fabricated [10]. Surface trapping effects can perform a similar function in preserving resolution [6, 7, 10, 12]. The reliance on trapping effects could impose a speed limitation, as in photoconductors; however, this will depend on the trap characteristics, such as field ionization and recombination effects.

Liquid crystals are the favoured spatial light modulator readout element because of low voltage, low charge and high resolution [12]. There are several alternative nematic liquid crystal readout schemes. The hybrid field structure adapts the twisted nematic effect to a reflective readout spatial light modulator situation [3, 8]. The surface mode configuration employs a non-twisted birefringence modulation, operated beyond threshold, to provide a faster response [12–14]. Alignment of a nematic liquid crystal, with positive dielectric anisotropy, perpendicular to the cell surface can provide a differentiating or edge enhancing photoaddressed device [15, 16]. Drive-on and drive-off should provide a speed advantage in this device, which

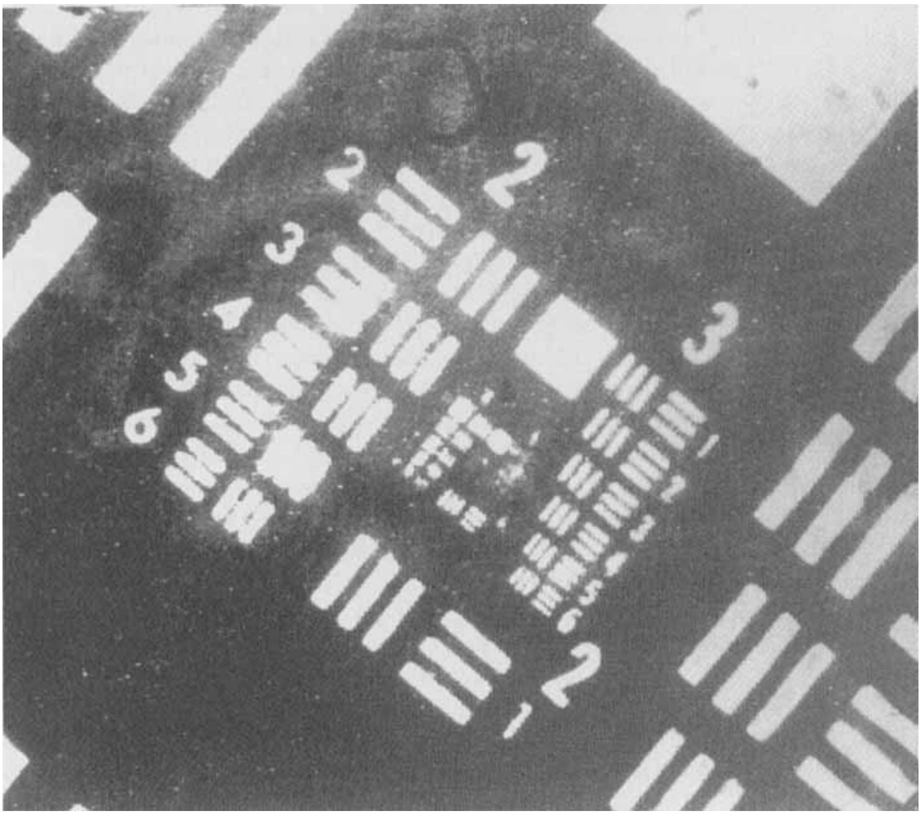

Figure 3. GaAs photoaddressed nematic liquid crystal spatial light modulator operated in the birefringent imaging mode. Output response to U.S. Air Force test target input; resolution of Group 3, No. 6 = 14·3 lp mm^{-1}.

exploits the transverse nematic response first demonstrated with electrode addressed structures [17].

The limiting frame rate of nematic spatial light modulators is less than 1 kHz. Ferroelectric liquid crystals that can satisfy the demand for higher frame rates are in the early stages of development [18–20]. Recent interest in the electroclinic effect and associated materials development could result in a faster response spatial light modulator with grey scale [21]. However, higher voltage levels in pursuit of faster response speed generally result in lower resolution, due to charge defocussing effects in the photoreceptor [9, 12]. Monocrystalline silicon or GaAs photoaddressing can provide the speed and voltage required to exploit the switching speed available now and in future ferroelectric liquid crystal materials. The first experimental results for a monocrystalline GaAs photoaddressed ferroelectric liquid crystal spatial light modulator are presented here.

2. Device fabrication and testing

The spatial light modulator configuration is shown in figure 2. The bulk of the structure consists of BK7 optical glass flats 50·8 mm in diameter by 12·7 mm thick. The flats are polished to 0·1 wave flatness over the central 25 mm diameter. The use of massive optical flats minimizes distortion in the assembly process and ensures the optical quality of the modulator. The outer surface are antireflection coated for 514 nm, and the inner surfaces are antireflection coated and provided with indium–tin oxide (ITO) transparent electrodes. The ITO electrode is extended over the edge area of the glass substrate by an evaporated chrome contact to facilitate electrical connection. A semi-insulating 50·8 mm diameter GaAs wafer, polished on both sides, is bonded to the substrate with a thin optical cement bond. The cement bond is about 2 μm thick and provides capacitive coupling to the wafer. The GaAs wafer is about 0·5 mm thick, but can be thinned by as required by further polishing of the mounted wafer. The mounted GaAs wafer can be polished to an optical flatness of 0·1 wave, which determines the limiting optical figure of the spatial light modulator. A multilayer dielectric mirror is evaporated on to the exposed GaAs surface.

Parallel alignment layers for the liquid crystal are provided by rubbed nylon coatings [22]. The cell thickness is defined by a Mylar spacer with an inner diameter of 31 mm, an outer diameter of 43 mm, and a thickness of 6 μm. The cell is assembled, with antiparallel rubbing directions, in a non-twisted state and filled with nematic mixture E7 (E.M. Chemicals) under vacuum conditions. The demountable assembly is clamped in a holder, which is accommodated by a standard 4 in. (10·16 cm) optical mount.

A slightly different assembly was used for the ferroelectric liquid crystal modulator reported here. The mounted GaAs wafer was lapped to a thickness of approximately 150 μm and polished to give a convex finish with the centre almost 12 μm higher than the boundary region. A 12 μm Mylar spacer provided a variable gap which was minimum at the centre. The substrates were assembled with parallel rubbing directions. The gap was filled, under vacuum, with the ferroelectric liquid crystal SEC4 (E.M. Chemicals), with the temperature raised to the chiral nematic range of SEC4 [23].

In the absence of write light, most of the applied voltage is dropped across the depleted GaAs bulk. The write light excites carriers, which are driven through the GaAs to accumulate at the mirror interface and raise the liquid crystal electric field. The input image is replicated by a charge distribution, where charge repulsion acts as a defocussing mechanism, which degrades the image resolution. In order to minimize loss of resolution due to charge migration, the device was operated under pulsed voltage conditions.

The capacitive coupling of the device implies A.C. operation, which is a general requirement of liquid crystals from electrochemical considerations [24]; however, any polarity dependence in the photoreceptor response creates a D.C. component in the device. The D.C. component charges the dielectric mirror capacitance via the liquid crystal ionic conduction, and this time constant can limit the response speed. The potential high speed and high voltage operation of GaAs photoaddressing could exploit the fast switching now available in ferroelectric liquid crystal materials. However, there are substantial differences in hole and electron transport and trapping in GaAs which result in polarity sensitivity and D.C. effects.

The spatial light modulator test bed, which has been described in detail, provides read and write optical pulses at 514 nm, in synchronous relation to the applied modulator voltage [10, 12, 19, 20]. T.V. cameras in the readout image and focal plane positions facilitate output analysis.

3. Results

The resolution and uniformity of the GaAs photoaddressed nematic modulator is illustrated in figure 3, which shows the birefringent image recorded on the readout

T.V. in response to the U.S. Air Force test target input. The spatial light modulator is driven by an A.C. coupled pulse voltage, where the pulse amplitude, width and frequency determine the r.m.s. bias voltage on the nematic. The contrast of the resultant output image can be varied from positive to negative by adjustment of the bias voltage.

A drive pulse polarity making the write input side positive, i.e. hole imaging, provides the sharpest resolution. The write light can be continuous, or pulsed with controlled width and position. Pulsed illumination coincident with or slightly in advance of the voltage pulse provides the best resolution. The test chart image in figure 5 corresponds to a voltage drive of 300 V, 200 μs pulses at 200 Hz. The write intensity was 80 μW cm^{-2} and pulse width 100 μs at 200 Hz. The GaAs wafer thickness was 0·4 mm and the nematic thickness was controlled by a 6 μm spacer. The visual resolution perceived on the T.V. camera approaches 25 lp mm^{-1}. A quantitative analysis of the modulation transfer function gives a 50 per cent modulator transfer function point of 10 lp mm^{-1}. Frame rates of 100 Hz have been demonstrated [12].

The imaging behaviour of a primitive GaAs photoaddressed ferroelectric liquid crystal modulator, without a dielectric mirror, is shown in figure 4. The liquid crystal thickness was estimated as 1 μm in the imaged area. The resolution and uniformity are inferior to the typical nematic modulator result indicated in figure 3. The modulator was translated to examine thicker regions of the ferroelectric liquid crystal, which were observed to be associated with lower readout resolution.

The flexibility of the addressing scheme is indicated in figure 5. The applied voltage waveform can alternate positive and negative with independent amplitude, pulse

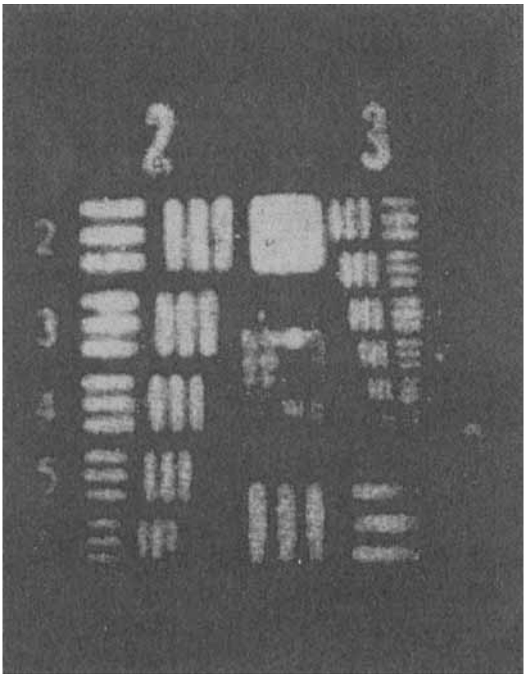

Figure 4. GaAs photoaddressed ferroelectric liquid crystal spatial light modulator operated in birefringent imaging mode. Output response to U.S. Air Force test target input; resolution of Group 3, No. 6 = 14·3 lp mm^{-1}

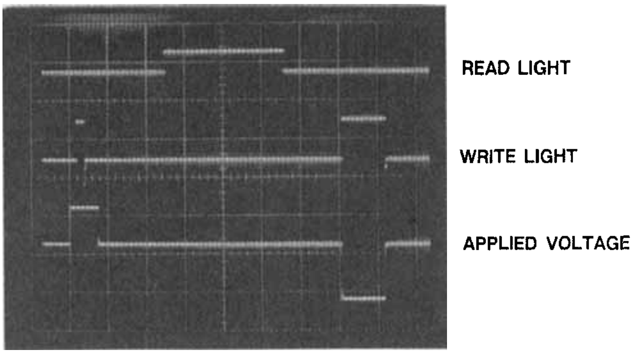

Figure 5. Voltage waveform and optical write and read pulses. (Upper) Optical read pulse, (centre) optical write pulse, (lower) applied voltage. Sweep speed 0·5 ms div^{-1}.

width and position on each half cycle. The capactive coupling of the device removes the average D.C. component. The optical write pulse is synchronized to the voltage pulse, but on the positive half cycle the pulse length and delay can be varied. There is also the option of dividing the write pulse rate. The optical read pulse is controlled in length and positive relative to the other pulses.

By varying the read pulse position, a write/erase frame speed of 3 ms was established. Capacitive coupling to the ferroelectric liquid crystal ensures a zero average D.C. level, but makes it difficult to control the potential at various points in the cycle. Charge trapping effects at the GaAs surface, transverse charge migration and lack of symmetry in the hole–electron transport generate spurious potentials which influence the ferroelectric liquid crystal response. These effects were offset by increasing the write light intensity to 1 mW cm^{-2}. The image resolution was sensitive to the read light strength, suggesting that the read light absorbed by the GaAs is significant in the imaging process. This was verified by off-axis auxillary illumination of the read side with an incandescent source, which restored the image clarity. The read light effect is interpreted as a photocurrent influence on the switching voltage at the ferroelectric liquid crystal.

A similar device was fabricated with an 85 nm evaporated coating of silicon dioxide on the GaAs surface interfacing the liquid crystal. The performance was similar to the performance of the first device, demonstrating that insulating the GaAs was not significant. After the second device was dismantled and cleaned, a sequence of amorphous silicon–oxide layers was deposited to form a dielectric mirror. The performance of the mirrored device was much poorer, and manipulation of the applied voltage waveform and write light to optimum conditions was necessary to discern an output image. The dielectric mirror transmits some of the incandescent auxillary light, but the image clarity could not be improved by this illumination. The mirrored device was dismantled, cleaned and reassembled with nematic E7, and was tested, with satisfactory imaging properties.

4. Conclusion

A simple capacitively coupled GaAs photoaddressed nematic spatial light modulator having good uniformity and reasonable resolution and speed has been demonstrated. The resolution is limited by charge migration in the GaAs. The next step in development is to incorporate etched groove dielectric barriers in the GaAs, which will improve the resolution [10, 12].

The initial experiments on the GaAs–ferroelectric liquid crystal modulator suggest that fast, high resolution devices can be developed. The charge required to drive the ferroelectric liquid crystal is significantly higher than the nematic. Moreover, the ferroelectric must switch every cycle, whereas the r.m.s. responding nematic can integrate over many pulse cycles. These distinctions explain why nematic photoaddressing structures may not suffice for the ferroelectric liquid crystal modulator.

The observed decrease in resolution with increasing ferroelectric liquid crystal thickness in the range 1–5 μm cannot be explained by electric field fringing effects [9, 12]. It is probably due to increased voltage levels caused by increased liquid crystal thickness at constant charge density. The increase in transverse electric field component, related to greater liquid crystal voltage, enhances the transverse charge migration, which is associated with loss of resolution.

The unusual behaviour of the read light on resolution is probably due to the release of trapped charge at the GaAs–ferroelectric liquid crystal interface. The lack of performance in the mirrored GaAs–ferroelectric liquid crystal spatial light modulator is difficult to explain. The mirror capacitance should not significantly change the electric field in the GaAs and liquid crystal. Contact effects should be discounted by the preliminary silicon oxide insulated coating experiment. More experiments are needed to establish the reproducibility of these effects and to clarify the influence of interfacial layers on the performance of the ferroelectric liquid crystal spatial light modulator.

The technical assistance of Steve Ichiki in thin film deposition is acknowledged. We are indebted to Don Kinell for advice on GaAs technology. The general comments and encouragement of Willy Anderson are appreciated. The work is supported by a Lockheed Missiles and Space Company, Inc., Research and Development Division program.

References

[1] Collings, N., 1988, *Optical Pattern Recognition Using Holographic Techniques* (Addison-Wesley).

[2] Armitage, D., Thackara, J. I., and Eades, W. D., 1988, *Proceedings 1st International FLC Conference, Ferroelectrics*, **85**, 291.

[3] Grinberg, J., Jacobson, A., Bleha, W. P., Miller, L., Fraas, L., Boswell, D., and Myer, G., 1975, *Opt. Engng*, **14**, 217.

[4] Ashley, P. R., and Davis, J. H., 1988, *Appl. Optics*, **26**, 241.

[5] Powell, M. A., Powles, C. M. J., and Bagshaw, J. M., 1988, *Proc. S.P.I.E.*, **936**, 68.

[6] Vasilev, A. A., Kompanets, I. N., and Parfenov, A. V., 1983, *Kvant. Electron.*, **10**, 1079 (*Soviet J. quantum Electron. APS*, **13**, 689).

[7] Dumarevskii, Yu. D., Kovtonyuk, N. F., Kompanets, I. N., Parfenov, A. V., and Petrovicheva, G. A., 1984, *Kvant. Electron.*, **11**, 730 (*Soviet J. quantum Electron. APS*, **14**, 493).

[8] Efron, U., Braatz, P. O., Little, M. J., Schwartz, R. N., and Grinberg, J., 1985, *J. appl. Phys.*, **57**, 1356.

[9] Armitage, D., Anderson, W. W., and Karr, T. J., 1985, *I.E.E.E. Trans. electron. Devices*, **21**, 453.

[10] Armitage, D., Thackara, J. I., Eades, W. D., Stiller, M. A., and Anderson, W. W., 1987, *Proc. S.P.I.E.*, **824**, 34.

[11] Hebbron, M. C., and Makh, S. S., 1987, *Proc. S.P.I.E.*, **825**, 19.
[12] Armitage, D., Thackara, J. I., and Eades, W. D., 1988, *Proc. S.P.I.E.*, **936**, 56.
[13] Bos, P. J., Johnson, P. A., and Koehler-Beran, K. R., 1985, *Molec. Crystals liq. Crystals*, **113**, 329.
[14] Fergason, J. L., 1986, *Proc. S.P.I.E.*, **684**, 81.
[15] Armitage, D., and Thackara, J. I., 1986, *Proc. S.P.I.E.*, **613**, 165.
[16] Armitage, D., and Thackara, J. I., 1988, *Appl. Opt.* (in the press).
[17] Channin, D. J., and Carlson, D. E., 1976, *Appl. Phys. Lett.*, **28**, 300.
[18] Clark, N. A., and Lagerwall, S. T., 1980, *Appl. Phys. Lett.*, **36**, 899.
[19] Armitage, D., Thackara, J. I., Clark, N. A., and Handschy, M. A., 1987, *Molec. Crystals liq. Crystals*, **144**, 309.
[20] Armitage, D., Thackara, J. I., and Eades, W. D., 1987, *Proc. S.P.I.E.*, **825**, 32.
[21] Bahr, C. H., and Heppke, G., 1987, *Liq. Crystals*, **2**, 825.
[22] Patel, J. S., Leslie, T. M., and Goodby, J. W., 1984, *Ferroelectrics*, **59**, 137.
[23] Bradshaw, M. J., Brimmell, V., and Raynes, E. P., 1987, *Liq. Crystals*, **2**, 107.
[24] Sussman, A., 1974, *Introduction to Liquid Crystals*, edited by E. B. Priestly, P. J. Wojtowicz and P. Sheng (Plenum Press).