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Laurent Dupont, Z. Y. Wu, P. Cambon, J. L. de Bougrenet de La Tocnaye. Smectic A and C* liquid crystal light valves. *Journal de Physique III*, 1993, 3 (7), pp.1381-1399. 10.1051/jp3:1993207 . jpa-00249006

HAL Id: jpa-00249006

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Submitted on 4 Feb 2008

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Classification

Physics Abstracts

42.30 — 42.70 — 42.80

Smectic A and C* liquid crystal light valves

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(Received 30 November 1992, accepted 22 April 1993)

Résumé. — Le développement des valves optiques dans le domaine de l'image et la représentation spatiale de l'information a bénéficié des progrès réalisés sur les matériaux « cristaux liquides ». Nous allons étudier tout spécialement les développements récents concernant l'utilisation des phases smectiques A et C*. Deux types de valves sont décrites avec leurs modes d'adressage respectifs : le modulateur à adressage optique : l'information est envoyée par voie optique et la commutation s'effectue par la conversion du signal optique en signal électrique grâce à une couche d'un matériau photoconducteur (silicium amorphe hydrogéné). Le deuxième type de valve est un circuit VLSI recouvert de cristal liquide pouvant être adressé par voie optique et effectuant un traitement logique local de l'information reçue ; la commutation locale du cristal liquide permet alors la lecture de l'état final.

Abstract. — The development of light valves for application in the domain of imaging and information display has benefited from simultaneous advances in liquid crystal materials. We will focus on recent developments involving the use of smectic A and smectic C*. Two types of light valves are described with their addressing technology. The first one is optically addressed spatial light modulator : optical information is converted into electric information through the medium of a photoconductivity material layer (amorphous silicon). The second type of valve is a VLSI chip covered with liquid crystal which can be optically addressed on each pixel and perform local electronic processing. The local switching of the liquid crystal allows the reading of the final state.

1. Introduction.

Optically addressable imaging devices, often referred to as light valves, have played a crucial role in adaptive optics and optical processing during the two last decades. The design of such devices is a direct consequence of the attention payed to real-time coherent optical processing during the seventies, concurrent with the development of coherent laser sources. One of the problems recognized early on was how to interface the coherent optical processors with the external world. The development of light valves for applications in the domain of imaging and information display, has benefitted from simultaneous advances in liquid crystal materials

such as nematic liquid crystals which asserted themselves very quickly as main candidates for modulating elements in light valve structures.

There are many possible light valve designs, and we do not wish to be exhaustive on the subject. We will instead focus on recent advances in liquid crystal light valves (LCLV), particularly those involving the use of smectic A and C* liquid crystal materials. For more exhaustive summaries of light valve structures, the reader may refer to the major contributions [1-5]. We will briefly discuss the current trends in these materials, particularly the various addressing modes that have been proposed. Finally, some examples showing how the devices are used in the field of information processing and neurocomputing will be presented.

2. Basic principle.

A light valve is an optical-to-optical image transducer capable of accepting a low intensity, white or monochromatic light input image and converting it, in real time, into an output image with light from another source. Generally the device is designed in such a way so that the input and output light beams do not interact. This gives the device great flexibility in its operating modes (e.g. allowing cascability). Several different structural combinations are possible. In particular, different modulating elements, and addressing layers have been proposed [6, 7]. As previously mentioned, we will only consider the use of liquid crystals as modulating element. The first liquid crystal modulator to be proposed was the nematic liquid crystal modulator.

2.1 LIQUID CRYSTAL MODULATOR DESCRIPTION. — The most commonly used liquid crystals are shaped like tiny rods. Depending on their temperature the rod-like molecules exist in different mesophases between the crystal state, and the completely unordered isotropic state of a liquid. When a liquid crystal is heated to above 100 °C, the molecules are randomly oriented and the solution appears isotropic. As the temperature decreases, the liquid crystal undergoes a phase transition from the isotropic to the nematic phase where molecules have orientational but not positional order. If the temperature is further reduced, the molecules begin to self-assemble into layers (the smectic phase). Therefore, at room temperature liquid crystals are anisotropic due to the ordering of the molecules in the liquid crystalline state [8, 9]. The easy reorientation of the molecules by externally applied electric fields allows a simple means of electrically controlling the optical properties of the phase.

A liquid crystall cell consists of a sandwich of thin films that electrically control the optical birefringence of a thin ($> 2\text{-}4\ \mu\text{m}$) liquid crystal layer. The general configuration is shown in figure 1. The ac light valve consists of a number of thin film layers sandwiched between two glass substrates. A low voltage (5-10 V_{rms}) audio frequency power supply is connected to the two outer electrodes (transparent thin film indium-tin oxide (ITO)) and thus across the entire thin film sandwich. The photoconductor and the light blocking layer form a rectifying heterojunction. The dielectric mirror and the blocking layer separate the photoconductor from the readout light beam (Fig. 1). This is one of the major benefits of the ac light valves : it enables simultaneous writing and reading of the device regardless of the spectral composition of the two light beams. A transmissive mode of operation is also possible, in which case the read beam must be chosen out of the absorption band of the photodetector, so that it does not erase the written information. In this case, light passes through the liquid crystal in one direction.

2.2 OPERATING CONDITIONS. — The twisted nematic light valve used in figure 1 is optically addressed by projection of an incoherent image onto the photoconductive material. The local illumination reduces the photoconductor impedance so that the ac voltage V applied to the cell *via* the two transparent electrodes is transferred to the electro-optic layer. The molecular

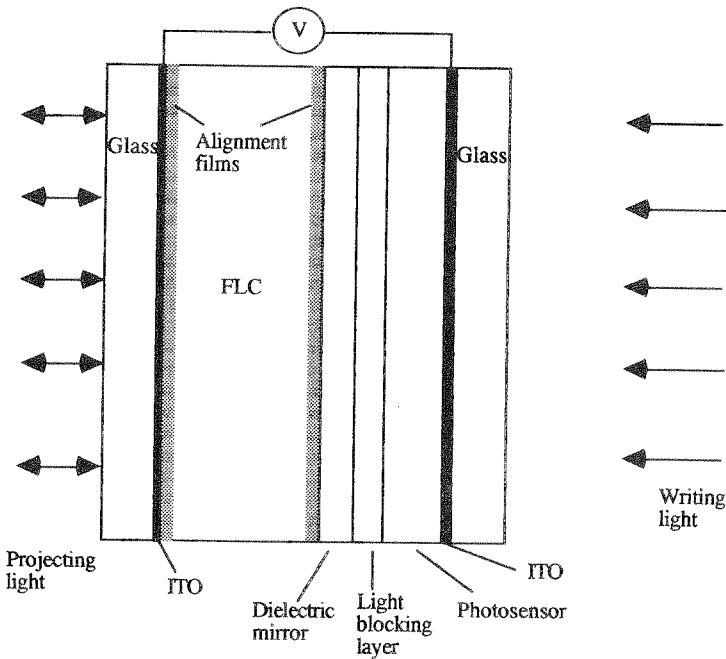


Fig. 1. — Cross-sectional schematic of the liquid crystal light valve (Ref. [1]).

reorientation induced by the electric field locally changes the liquid crystal birefringence and thus spatially modulates the phase of the incident coherent light beam at wavelength λ . In this particular mode of recording, the incoherent image is converted into a coherent wavefront having a spatial phase shift $\Delta\varphi$ between two linearly polarized components according to the relation :

$$\Delta\varphi = 2 \pi e \Delta n [I(x, y) ; V] / \lambda \tag{1}$$

where e is the liquid crystal thickness, $\Delta n [I(x, y) ; V]$ is the photoinduced birefringence change of the liquid crystal due to illumination of the light valve by $I(x, y)$, and V is the bias voltage applied to the transducer. Molecules in the bulk of the liquid crystal layer rotate through the angle of twist between the electrodes. This twisted alignment configuration, combined with the intrinsic optical birefringence of the liquid crystal, causes the polarization direction of a linearly polarized incident light to rotate exactly through the twist angle.

When no electric field is applied, as shown on the right hand side of figure 2, the orientation of the nematic liquid crystal molecules is twisted a total of 90° between the two electrodes. In figure 2, we assume that the light input is from the top of the cell. After passing through the polarizer, only the 0° component of the light continues to propagate. The polarization of the light is rotated a total of a 90° by the liquid crystal molecules and then blocked by the 0° polarizer, yielding a dark output which means that the cell is OFF. When the applied electric field is not 0, as shown on the left-hand side of figure 2, the molecules are made to tilt towards the direction of the electric field, and in the extreme case can be made perpendicular to the electrodes by applying enough voltage. In this condition, the orientation of the input light is able to pass through the 0° polarizer, so the output is bright and the cell is ON. When the voltage is below this extreme, the tilt angle of the molecules reduces the rotation angle of polarization of the light passing through the layer. Thus the input-output can be controlled by

the applied voltage. This means that an amplitude modulation can be obtained when the cell is placed between two crossed polarizers. As simplified expression for the transmittance T has been derived theoretically [10] w.r. to the configuration of figure 2 :

$$T = T_0 \sin^2[\pi e \Delta n \phi (V)/\lambda] . \quad (2)$$

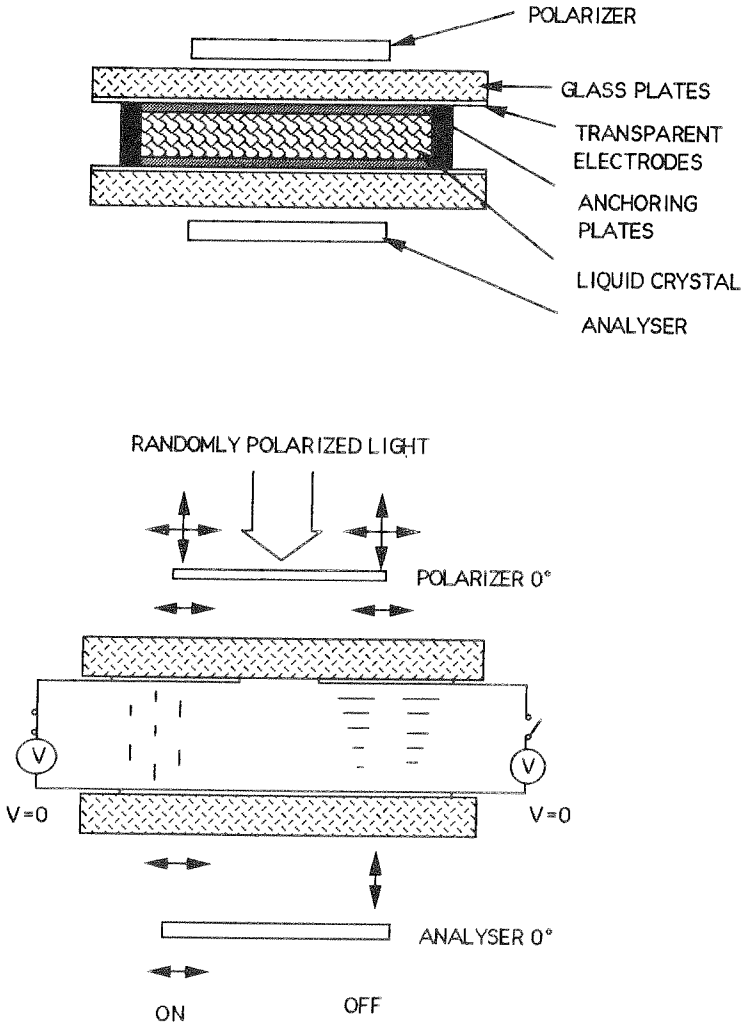


Fig. 2. — Two cases of the light transmission property of the liquid crystal cell.

The transmittance T will thus vary with the voltage V , for a given twist angle $\phi \leq \pi/2$. Using this principle, logic operations based on polarization encoding have been proposed [11]. The interesting point here is that an intensity variation is converted into an amplitude variation expressed by the transmittance T .

The principle of the twisted nematic mode is based on the fact that the electric torque has a quadratic dependence on the external electric field. This physical behavior implies that the OFF state response time depends on the electric field magnitude, while the ON state relaxation

time is intrinsic to the twisted nematic [12]. The rise and decay times are given by :

$$\begin{aligned}\tau_{\text{decay}} &= \eta/Kq^2 \\ \tau_{\text{rise}} &= \eta/|\varepsilon_a E^2/4 \pi - Kq^2| \end{aligned} \quad (3)$$

where η is the twist viscosity, ε_a is the dielectric anisotropy, K is the elastic constant function of E , and $q = \pi/d$ (where d is the cell thickness).

This relaxation time (τ_{decay}) is the main limitation in the response time for nematic materials. Typical response times of 10 ms are measured.

3. Smectic C* and A liquid crystal light valves.

As seen above, the smectic phase is characterized by layered structures which appear when the temperature decreases. If the long axis of the rod-shaped molecules is perpendicular to the layers, the phase is called smectic A. Lowering the temperature further can cause the molecules to tilt at an angle θ with respect to the normal of the layer, forming the smectic C phase, the most ordered and least symmetric liquid crystal phase. A lack of symmetry is needed to make the liquid crystals ferroelectric, that is to possess a spontaneous polarization. Meyer *et al.* recognised in 1974 [13] that making the liquid crystals chiral (i.e. unable to be superimposed upon their mirror image by rotation, translation or reflection) removes the liquid crystal mirror plane symmetry thus producing microscopic ferroelectricity.

3.1 FERROELECTRIC MODE (GOLDSTONE MODE). — Chiral smectic (Sm C*) liquid crystal could have a spontaneous polarization P_s . The major advantage of this mode is the high ferroelectric coupling between the external electric field E and P_s . The smectic C* are layered structures where two parameters are needed to describe the physical properties: the spontaneous polarization P_s and the long molecule director axis n , which is a function of the tilt angle θ and the azimuthal angle ϕ (Fig. 3). Nevertheless, the spontaneous polarization of the material cannot be observed directly because, as a result of the chirality of the phase, a spontaneous helix is formed in which the director axis precesses around the normal of the layers. As a result the polarization is averaged out.

In 1980, Clark and Lagerwall demonstrated the possibility of obtaining a fast switching device with a thin film liquid crystal (called the SSFLC for surface stabilized FLC) where the layers were perpendicular to the electrode [14] (Fig. 4). The basic idea was to prevent the helix formation by a confinement between two glass plates. In the SSFLC structure, due to the strong anchoring of the liquid crystals at the electrode interface and the small thickness of the cell, the helicoidal structure cannot form because the twist and chiral energy become

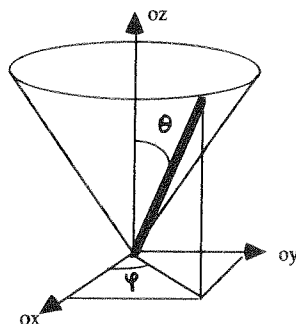


Fig. 3. — Director fluctuations in the C* phase with constant tilt angle (Ref. [13]).

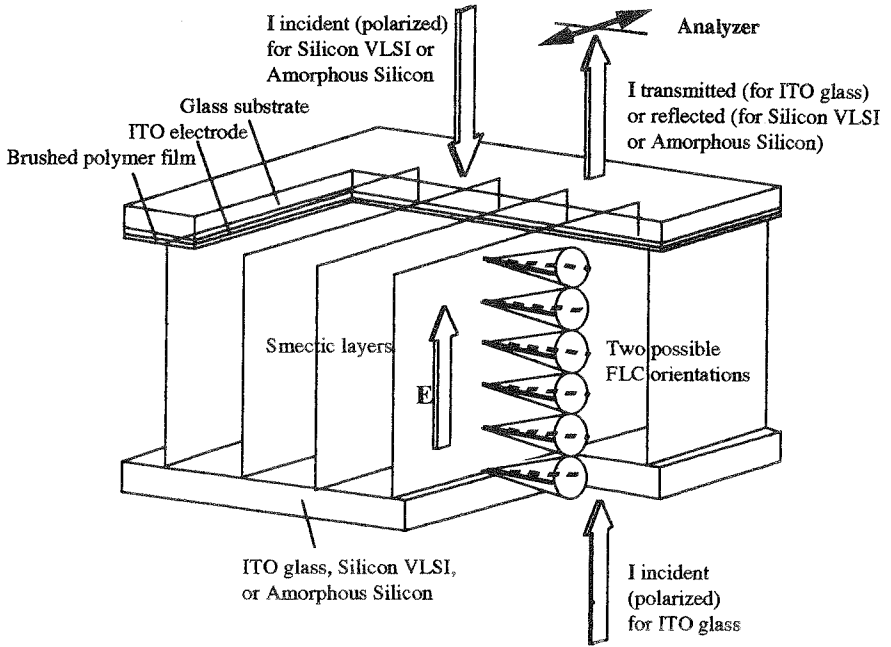


Fig. 4. — Ferroelectric liquid crystal cell configuration.

negligible. In this case, the expression of the Landau free energy F near the smectic A-smectic C^* transition is independent of the azimuthal angle ϕ , so F is degenerate on the smectic cone. The SSFLC structure is a twofold degenerated system. In addition to the constraint that the director must lie on the surface of the smectic cone, there is the constraint that it must be parallel to the bounding glass plates. This means that only two positions are possible for P_s , and the position of n depends only on the direction of the electric field, and on the anchoring of the liquid crystal molecules at the surface. This is the main cause of the bistability.

If the polarization of normally incident light is chosen either parallel or perpendicular to one of these voltage-selected optical axis states, it will be transmitted unaltered. When the other optical axis state is selected by applying a voltage of the opposite sign, the optical axis is rotated to a $\pi/4$ angle from the incident polarization (in the case of a tilt angle $\theta = 22.5^\circ$) so that both the ordinary and extraordinary modes are excited. Figure 5 illustrates this action of the FLC electro-optic element. The transmission of light through the FLC is thus described by the following equation (Fig. 5) :

$$T = \sin^2(4 \theta) \sin^2(\pi e \Delta n / \lambda) . \tag{4}$$

The ferroelectric dynamic mode, in the uniform structure, can be described by the Sine-Gordon equation, if the term for the dielectric coupling and elastic term (gradient term) are neglected :

$$\gamma_\phi \delta \phi / \delta t = - P_s \cdot E \sin \phi \tag{5}$$

where γ_ϕ is the azimuthal viscosity. From (5) we can derive the characteristic electric field dependent response time :

$$\tau = \gamma_\phi / P_s E . \tag{6}$$

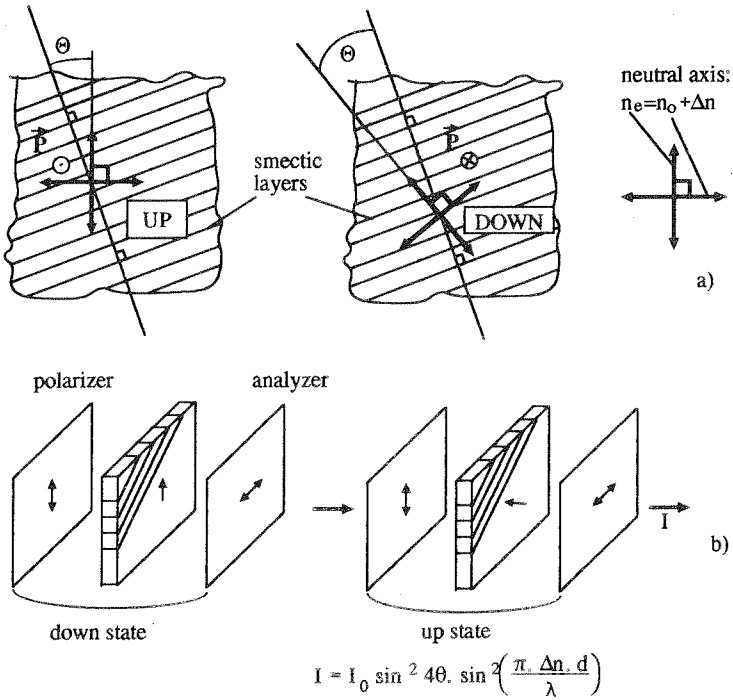


Fig. 5. — Use of a FLC cell as programmable half wave plate.

The difference from the nematic case is thus the symmetry of the response time (i.e. the device can be switched actively in the « ON » and « OFF » states). This is the basis of the faster switching time obtained with the FLC. Typical values of 10-100 μ s or less are measured [14]. This property, together with the intrinsic bistability, are the two original properties of FLC materials.

3.2 ELECTROCLINIC MODE (SOFT-MODE). — In the smectic A phase, a tilt angle can be induced by an applied field E [15]. The structure is the same as the SSFLC, but the alignment of the liquid crystal is better than in the smectic C* (no chevron structures). The existence of this electroclinic mode is due to the coupling between θ , P (the induced electroclinic polarization) and E in the phenomenological Landau free energy expansion :

$$F = \frac{1}{2} \alpha (T - T_c) \theta^2 + \frac{1}{2 \epsilon_0 \chi_{\perp}} P^2 - cP\theta - PE + \dots \tag{7}$$

where c is the linear coupling between P and θ , $\alpha (T - T_c)$ is the elastic modulus which depends linearly on the temperature in a first approximation. χ_{\perp} is a generalized susceptibility.

At equilibrium we obtain the relations :

$$\frac{\partial F}{\partial \theta} = \frac{\partial F}{\partial P} = 0 \Rightarrow \begin{cases} \theta = \frac{\chi_{\perp} c}{a^*} E \\ P = \frac{\chi_{\perp}^2 c^2}{a^*} E \end{cases} \text{ with } a^* = \alpha (T - T_c^*) \tag{8}$$

T_c^* is the renormalized transition SmC*-SmA temperature for chiral compound. This means that there is a linear relation between θ , P and E . This linear relation is crucial because it is the basis of the formation of grey scales. The dynamic equation is given, in this case, by the following Landau-Khalatnikov relations :

$$\begin{aligned} \gamma_\theta \frac{\partial \theta}{\partial t} &= - \frac{\partial F}{\partial \theta} \\ 0 &= \frac{\partial F}{\partial P} . \end{aligned} \quad (9)$$

Where γ_θ is the soft-mode viscosity. The dynamics of the soft mode looks like a Lorentzian relaxation, from which we reduce the characteristic response time of the electroclinic mode :

$$\tau_{\text{elec}} = \gamma_\theta / a^* \quad (10)$$

which is independent of the external electric field value. This mode has a critical temperature behaviour near the SmA-SmC* transition. The divergence of the response time follows the law :

$$\tau_{\text{elec}} \approx \frac{1}{(T - T_c^*)} . \quad (11)$$

In the soft mode, the highest contrast is associated with the smallest speed : a compromise must be found. This implies good thermal regulation to perform the dynamics.

Typical switching of 1-10 μs can be observed, making the soft mode the fastest liquid crystal electrooptic effect [15].

3.3 BISTABILITY AND GREY LEVEL ON SMECTIC C*. — Although SSFLCs are basically bistable devices, it is possible to obtain grey levels under certain driving conditions [16] (e.g. for an under critical value of the product of height and length of the applied voltage). Under these conditions, the cell does not switch uniformly, but shows a grainy structure due to the appearance of small black and white domains. Averaging the optical response over a given area results in a grey level. One advantage of creating grey levels with bistable devices instead of other materials like nematics or smectic A is the memory of the device. The grey level can be stored, and in the case of an optically addressed spatial light modulator (OASLM), optically read and modified. This is a very powerful property for a large number of applications in optical computing and display [17].

The grey level operation is due to multi-domain switching, as described in [18]. Switching by wall propagation is less energy consuming than uniform switching. The spatial distribution of switched domains is determined by the more or less random distribution of defects in the smectic layers structure which act as nucleation sites for the domains. Another interesting property is the linearity of the process. It has been shown [16] that the grey level process is linear when charge controlled and strongly nonlinear when voltage controlled as when used with photoconductor addressing.

3.4 THE PERFORMANCE OF LIQUID CRYSTAL LIGHT VALVES. — The performance of the liquid crystal light valve for optical data processing applications is measured by the following parameters : contrast, resolution, linearity, response time, optical flatness and image quality.

Contrast. — This feature is very critical because it allows, together with the linearity, possible information enhancements in cascaded architectures. The contrast is the maximum ratio of the polarized light intensity passing through the valve at state ON to that at state OFF. In the case of nematic materials, it is mainly limited by the voltage value necessary to tilt the molecules. It

can be altered principally by liquid crystal defects. This is the case for FLC materials where the so-called zig-zag [19] or other kind of defects can appear if appropriate alignment techniques are not used. Contrast value ranging from 20-500:1 can be typically expected with standard FLC OASLMs [20]. At Boulder contrast ratios that exceed 1 000:1 for a laser beam of 1 mm diameter have been measured for individual optical shutters [20].

Linearity. — For most modulators, the contrast is not a linear function of the writing beam intensity. Firstly, they are used in conjunction with crossed-polarizers which produce an output intensity proportional to the square of the sine of the input intensity. Secondly, for the photo-addressing layer its photoconductivity is a non-linear function of the illumination [21, 22]. The variation of the photoconductivity can be described as :

$$\sigma_{ph} = \sigma_0 F^\gamma \quad (12)$$

where σ_0 is a prefactor and F is the illumination intensity. For amorphous silicon, when F is in the order of 0.1 to 10 $\mu\text{W}/\text{cm}^2$, $\gamma > 1$ and the photo-conductor operates in the so-called super linear region ; in most cases $F = 10 \mu\text{W}/\text{cm}^2 - 10 \text{mW}/\text{cm}^2$, $\gamma = 0.7-0.9$ [23, 24] ; if $F > 10 \text{mW}/\text{cm}^2$, γ is about 0.5. The voltage applied to the liquid crystal is the difference between the valve total voltage and the voltage applied to the photo-addressing layer. When amorphous silicon is illuminated, the voltage applied to the liquid crystal increases. Naturally the voltage, and therefore the contrast, vary non-linearly with the intensity of the writing beam (see Fig. 6). Initially the contrast increases nearly linearly with the writing beam intensity, after that, it reaches saturation, where the OASLM current is limited by the FLC resistance and almost all of the valve voltage is applied to the liquid crystal. It should be mentioned that because of the dependence of photoconductivity on the Fermi level position, the semiconductor/contact interface may change the slope of the arising part of the contrast and the repartition

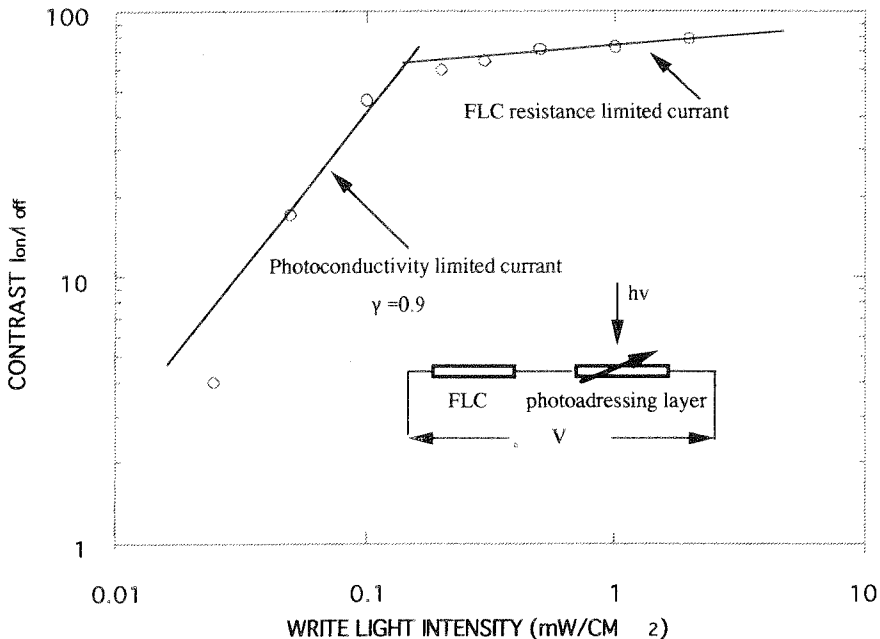


Fig. 6. — The non-linear behaviour of the contrast *versus* the intensity of writing beam.

of the voltage between liquid crystal and photon-addressing layer may shift the transition of contrast saturation.

Another important category of SLM nonlinear operations is image thresholding. To start writing, every valve has a minimum voltage applied to the liquid crystal. In the OASLM case, there is a writing beam intensity which corresponds to the minimum voltage. As explained above, this threshold writing intensity is determined by the photoconductivity behavior and the repartition of the voltage between the photo-addressing layer and the liquid crystal and therefore can be tailored according to the choice of materials and the design of this modulator.

Resolution : (given at 50 % MTF). — It is a critical feature for 2D processing because it determines the parallel processing capacity of the device. In the case of light valves, two features have to be considered : the photo-addressing layer and the liquid crystal itself. As far as the photo-addressing layer is concerned, to have a good resolution one has to prevent transversal leakage of charges from illuminated lines to its nearest dark neighbours, in other words, the resolution is dependent on the square resistance and the thickness of the photo-addressing layer. Obviously, the higher the resistance and the thinner the layer, the better the resolution will be. If the photo-addressing layer is compensated amorphous silicon of 10^{-12} (ohm-cm) $^{-1}$ and 5 000 Å thickness, the resolution may be as high as 150-180 lp/mm. Concerning the liquid crystal, its conductivity is of the order of 10^{-9} - 10^{-10} (ohm-cm) $^{-1}$; the thickness is about 2 μm, the resolution is limited by the domain size, in the case of FLC. The role of other layers such as dielectric mirror and alignment coatings can be neglected. A spatial resolution of 40 lp/mm at 50 % MTH has been measured for the FLC OASLM described in [20] and [21], while a resolution of 125 line pairs per mm is generally given in the case of a FLC SLM or display.

Response time. — It is of particular interest, for example, when the device is optically addressed. Typical switching times of 10-100 μs can be obtained with smectic C* FLC and switching times of 1-10 μs with smectic A. This is related (Eqs. (6) and (9)) to the value of P and γ_{θ} . Experimental mixtures have achieved $P > 500$ nC cm $^{-2}$. These improvements would result in microsecond switching speeds at 25 °C, and 120 ns at higher temperatures. Concerning the viscosity γ_{θ} , the energy dissipated by the viscous motion of the molecular director is likely to limit the switching speed. A typical value for FLC material viscosity in a room-temperature device is 50 cP. For a reflection mode device of thickness 1 μm, if the device can dissipate 10 Wcm $^{-2}$, switching speeds of 1.3 μs at room-temperature and 130 ns at elevated temperature ($\gamma_{\theta} = 5$ cP) are possible [25].

Nevertheless in the case of light valves, the response time is related to the structure. In a photoconductor configuration, the response time may be rather long. Because in microcrystalline or amorphous semiconductors, carriers are captured and emitted by shallow traps during the transport, the transport being a dispersive process [26]. A photoconductivity decay is thus formed. The response time depends on the trap density. If one uses a photodiode structure as the photo-addressing layer, a built-in field controls the whole thickness of the layer, carriers are collected more easily. The response time decreases considerably. This is the reason why photodiode or phototransistor structures are preferable with FLC.

Finally, optical flatness (measured with an interferometer) and the image quality should not be neglected. In practice, this involves principally technological excellence. Furthermore, a coherent optical SLM is naturally more demanding in flatness, so that sophisticated planarization is required.

4. The main addressing modes.

As mentioned previously, a light valve is a combination of two elements : the addressing layer and the light modulator. The addressing layer is critical not only because it determines the operating functionality of the complete device, but also because it will influence directly the electrical and physical behaviours of the complete device. This point should not be underestimated when assigning to the device its characteristics. In practice, this imposes compromises between speed, sensitivity, absorption, resolution, etc. Furthermore, external constraints resulting from the system in which the device is inserted, have to be considered (operating wavelength, cascability, etc.). Basically, there are two main addressing modes. The massive one (using the bulk crystal) and the pixelated one. The latter can be divided into three categories : electrical addressing, optical addressing and smart addressing.

4.1 THE ELECTRICAL ADDRESSING. — There are three methods for electrically addressing an FLC SLM : direct drive, matrix and silicon backplane addressing. In direct drive addressing, each pixel in an array has a separate electrode. In matrix addressing, transparent row and column electrodes are etched onto separate glass substrates. The pixel is defined as an overlap of a row and a column electrode. Only $2N$ electrodes are required to switch N^2 devices. The silicon backplane uses a parallel addressing scheme, which is detailed in [27]. The fabrication of liquid crystals on top a silicon integrated circuitry was pioneered by Vass at Edinburgh University, Crossland at BNR Europe and commercial prototypes have been produced by Toshiba, Hughes Aircraft and STC Technology [27]. The first example of a FLC/silicon backplane display used a DRAM addressing of 240×240 pixels on a $60 \text{ mm} \times 60 \text{ mm}$ die. It was designed as a handheld data display [27]. This addressing scheme does not belong properly to the standard category of light valves, it concerns the category of digital to optical converter. Nevertheless, it is interesting to mention it because such a device was the basis of the recent advances in the domain of smart light valves and retina (see Sect. 4.3).

4.2 THE PHOTO-ADDRESSING. — This configuration corresponds properly to what is commonly called a light valve. In an optically addressed SLM (OASLM), a write beam carrying spatially varying information, is absorbed by the photosensor and the SLM modulates either the phase, polarization, intensity or wavelength of a read-beam. The information can be stored using either slides or CRT. Several groups have produced OASLMs coupling hydrogenated amorphous silicon [28], or GaAs [29] photosensors with FLC modulators. As a photosensor, the a-Si:H has been shown to have many advantages over crystalline photosensors. It has an excellent ratio of photoconductivity ($10^{-4} \text{ (ohm-cm)}^{-1}$ under 100 mW/cm^2 illumination) over its dark conductivity (say, $10^{-9} \text{ (ohm-cm)}^{-1}$ for the undoped ; $10^{-12} \text{ (ohm-cm)}^{-1}$ for the compensated) according to which OASLM can have a good signal/noise. Amorphous silicon has also a coefficient of absorption of an order of 10^4 - 10^5 cm^{-1} at visible region. A photo-addressing layer of just several thousands angstroms is thick enough. This thickness allows us to obtain a high resolution. And lastly, the plasma CVD technique can now be used to deposit hydrogenated amorphous silicon at a low temperature to form a layer with an uniformity as good as 1-2 % over a substrate of $30 \text{ cm} \times 30 \text{ cm}$.

When using a truly bistable OASLM, a light beam can operate either in a reflective or in a transmissive mode. In the transmissive mode, a compromise between the quantum efficiency (i.e. the write sensitivity) and the transparency or absorption has to be found. In practice, this purpose supposes the deposition of thin semiconductor layers. Fortunately, this acts in favour of high resolution. Concerning the device speed, it is limited by the photoconductor. This is generally not a limitation when using a nematic OASLM, because the switching speeds are comparable to that of the relaxation time. However, when using FLC materials, the

photodetector response speed could become a limiting factor. Such a consideration has given rise to original contributions in the field of the design of fast speed light valves. Model was the first to propose associating a bistable FLC with an amorphous silicon p-i-n structure [30]. We have ourselves proposed a p-i-n-i-p or n-i-p-i-n symmetric structures (Fig. 7). These structures give a symmetric photo I - V characteristics which are compatible to the bistability of FLC. Furthermore, they have a good time response. Experiments carried out on such a device have shown repetition rates faster than 20 kHz for an addressing light power of about 25 mW/cm^2 [31].

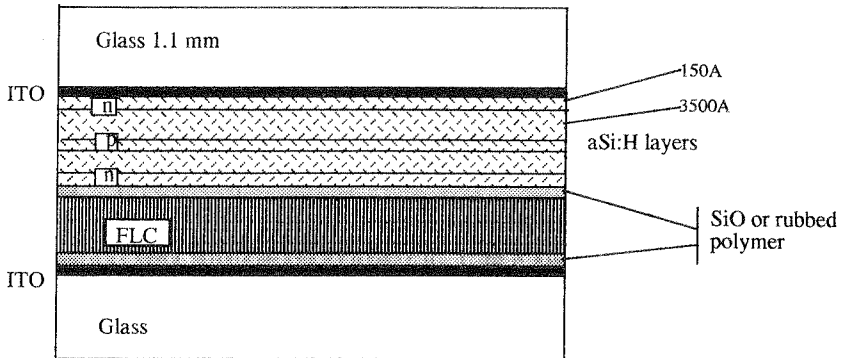


Fig. 7. — Light valve using n-i-p-i-n a-Si:H structure with bistable FLC.

4.3 THE SMART ADDRESSING. — This device can still be considered as a light valve, because of the optical to optical conversion, although this conversion is performed separately on each pixel. This means that each pixel operates independently as a small light valve. Furthermore, in this case, the conversion operation is more complex because intermediate electronic processings can be included during the process (e.g. nonlinear processings [32]) as well as the interaction with the neighbours. This is a reason why the device is called a smart light valve. Smart OASLMs have been fabricated using silicon VLSI backplanes [32, 33]. Figure 8 shows the principle of a such device which combines silicon junction phototransistor as detectors, silicon CMOS analog circuitry, and FLC binary light modulator cells driven directly by the circuitry. Such devices have been proposed to perform, for example, (32×32) image thresholding functions. Switching energies of FLC materials are typically a few fJ/mm^2 , and switching speeds in tens of microseconds can be contemplated for binary FLC modulators driven from a silicon VLSI die. Analog operation at comparable switching energies and speeds is expected from smectic A materials. Although CMOS logic speeds are much higher than FLC switching rates, the low static power dissipation of silicon CMOS logic permits a sub-picoJoule speed-power product to prevail at low clock rates. This reciprocity allows CMOS circuitry to operate at rates matching liquid crystal switching times (10^3 - 10^5 Hz) without suffering an increase in switching energy.

Regarding the possibilities of VLSI circuits, more complex designs may be addressed. For example, each pixel can be coupled to a local programmable processor or interconnected with other pixels following a given neighbourhood function. Binary Mathematical Morphology retina [34], or cellular automata [35], have been implemented or studied following this principle. Here, in comparison with the above mentioned devices [32, 33], each cell has been interconnected with other cells, therefore allowing a considerable system complexity,

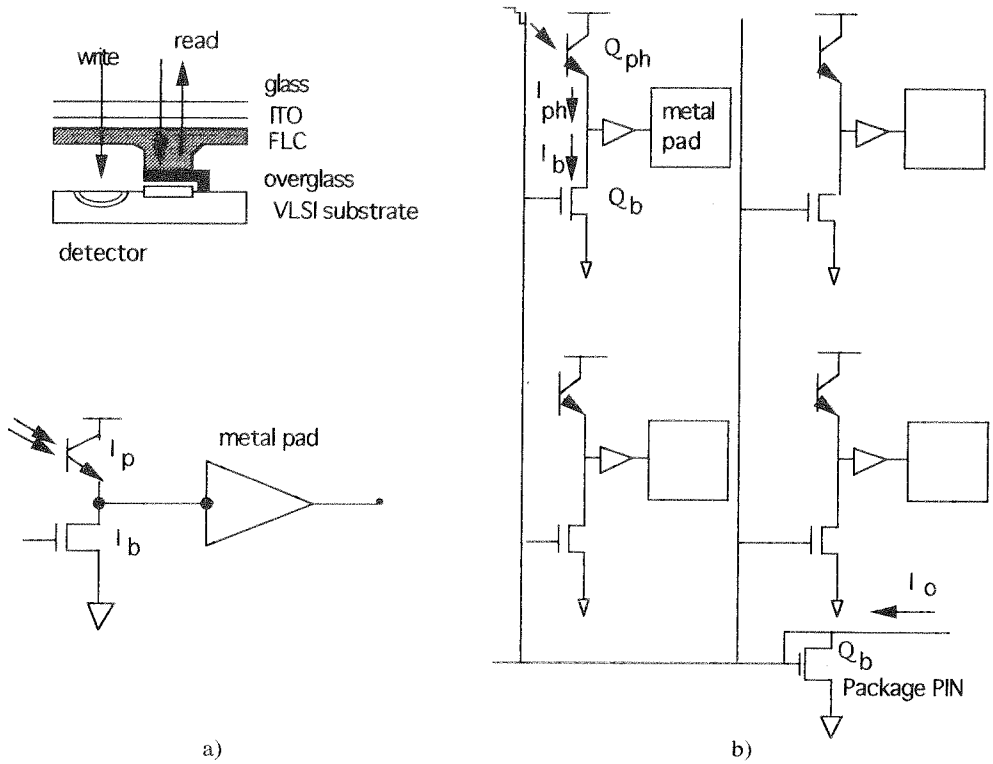


Fig. 8. — Principle of the photoaddressable silicon VLSI/FLC light valve. a) cross section of the VLSIO and functional circuitry, b) schematic circuit diagram of thresholding array (Ref. [26]).

involving, for instance, the implementation of local image processing or cellular automata. In such smart light valves, cell interconnections can be carried out either electronically or optically. For local interconnections (e.g. the nearest neighbourhood) electrical solutions are preferable. This is the case for the retina [34] on which FLC has been deposited successfully [36]. Figure 9 shows a photograph of several cells on the present chip. This chip supplied by the Institut d'Electronique Fondamentale in Orsay, is a silicon chip using 2 μm CMOS technology. Each elementary cell is 95 μm \times 95 μm , and the retina is a matrix of 64 \times 64 elementary cells, yielding an overall size of 7.2 mm \times 7.2 mm. Each cell consists of a photodiode, two memory points, and a transistor coupled logic (TLC) circuit. The photodiodes are silicon photodiodes having a size of 30 μm \times 30 μm . The TLC circuit allows programming of the shifts (up, down, left, right), and assures the interconnections between the pixels. A glass plate with the transparent counter-electrode has been placed on the chip, and the space between the two parts has been filled with smectic C* liquid crystal (Fig. 9).

During operation, the component is illuminated with an image. Photodetectors binarize the image using a pre-set threshold, and memorize it. The exposure time is determined by an average intensity. Each mirror receives a voltage corresponding to the binary value of the pixel, and the voltage difference between the mirror and the counter-electrode determines whether or not the liquid crystal above the mirror will switch. During reading, a uniform and linearly polarized incident light beam is reflected by the mirrors and modulated by the liquid crystal. A polarizer above the liquid crystal layer transmits or absorbs the reflected light, depending on the modulation. There is no voltage applied to the photodiodes during the

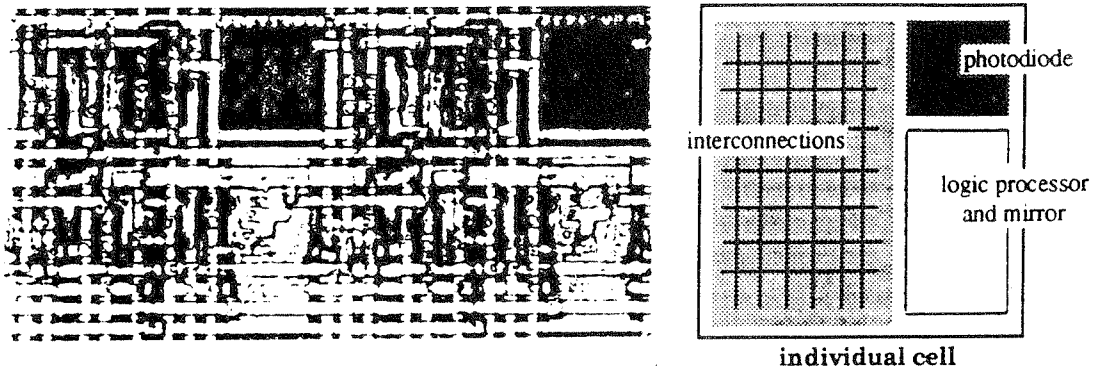


Fig. 9. — Photograph and schematic of two cells of a 64×64 Mathematical Morphology retina.

reading, so the memorized information is not erased. This is particularly interesting, because intrinsic memorized FLC states are not required.

Depositing FLC onto silicon VLSI chips presents several challenges. First, in order to obtain maximum contrast between the two switching states, the liquid crystal must have a thickness corresponding to a $\lambda/4$ phase delay. One way to achieve this thickness technologically is to use a fixed binding to hold the assembly in place while the glass is being glued onto the chip. Another solution is to use spacers. The achievable optical quality of the device will be limited by the rough surface of the circuit and by the placement of the mirrors. For the chip to be compatible with coherent illumination, the mirror surfaces must be optically flat and co-planar with the chip surface. Another concern is the possibility of false switching of the liquid crystal due to the difference in potential between the circuit and the counter-electrode. Such a problem must be minimized by a proper circuit design. In the present photodiode configuration it has been possible to place the glass directly onto the mirrors, thus using the mirrors as spacers and the photodiode surfaces themselves as the reflectors beneath the liquid crystal layer.

5. Some domains of applications.

A large number of applications, based on the use of FLC light valves [37], have been proposed, like a novelty filter [38], the Lyot filter [39], second harmonic generation, and phase conjugation [40]. Another interesting investigation has concerned the implementation of computer generated 2-D phase only hologram recorders [41]. Nevertheless, an exhaustive review is quite impossible. We have decided to focus here on two applications. The first concerns the domain of information processing and more precisely the implementation of real-time Joint Transform Correlator (JTC). A recrudescence of attention has been paid for such an architecture, in the last two years, due principally to device improvements (i.e. in contrast, nonlinearity, and speed), resulting from the supply of fast FLC light valves and EASLMs [42]. The use of fast switching elements allows a time multiplexing of the references with respect to the video rate. Taking into account a reasonable device development, time multiplexing of 50-100 different references for each video scene can be expected, when using, for instance, a silicon backplane EASLM for inputting the references [43]. The second improvement is due to the use of a FLC bistable OASLM (BOASLM) in the Fourier plane. Although the dynamic range of the nonlinear response is limited, experimental results have shown that this feature can be adjusted [44, 45]. Increasing the severity of the nonlinearity is well known to improve the discrimination capability. Such devices have been successfully used to enhance the correlation peak and therefore to improve the detection performance of standard correlators.

The second kind of promising applications of FLC light valves concerns the domain of complex systems and neural computing. A review of the main capabilities of FLCs for neural implementation has been presented by Johnson in [46]. Requirements for optical neurocomputing are similar to those of digital optical computing, except that high frame rates are not essential. FLC light valves can be used in neurocomputing as input-output display, storage medium for the synaptic weight as well as nonlinear elements for decision making. The critical step of neural net optical implementations is the learning process and more precisely the weight encoding and updating. To encode weights, grey levels are needed. Although the FLC devices are binary devices, grey levels can be achieved by temporal, and/or spatial multiplexing. A supervised learning algorithm has been implemented in storing the connection weights as pixels in a EOASLM [46]. The trade-off is, in this case, between encoding capacity and control.

All optical alternatives exist. Smectic A materials are also very promising in this domain. Because they provide a linear modulation of light in response to an applied field and permit a high switching speed independent of grey levels, smectic A EOASLMs potentially have all the operating characteristics necessary to build large size fully interconnected neural network architectures with grey level capability [47]. The major problem in this case is related to the unipolar encoding of the weights (because of using a polarization encoding). This has given rise to ingenious solutions using basically two polarization encoding channels [48, 49].

Another solution using smectic C* and aiming at taking advantage of the multi-domain switching of EOASLMs to implement the weight encoding and updating has been proposed [50]. In this manner, the value of the grey level may be stored, increased or decreased. The spatial accumulation capability of the device, together with possible thresholding of the image bearing light beam, allows the memorization, accumulation, and erasure of pictures. The device performs basically a logic OR between successive picture exposures. Data can therefore be successively recorded with varying gains. The value of the gain depends on the apparent sensitivity of the device and can be influenced by varying the electrical driving parameters of the EOASLM. In order to store independent weights with a sufficient amplitude range, a minimal FLC area of $100 \times 100 \mu\text{m}$ is necessary. This would allow storage of about 10,000 weights/cm² using a conventional EOASLM. Taking into account this capability, a learning process which can be assimilated to the hetero-associative memory principle has been proposed [51], making this approach close to that using photorefractive materials. The difference to the latter is related to the fact that information is spatially stored in a matrix of weights (the EOASLM) instead of being stored in the volume. The EOASLM acts like a photographic plate subjected to multiple exposures and used as a 2-D hetero-associative long term reconfigurable memory.

To be complete, we may mention that FLC light valves can be also used to implement decision steps in neural architectures. A good example can be given by the implementation of the Winner Takes All (WTA) algorithm. Nevertheless, a proper WTA function is well known to be difficult in implementing conventional nonlinear-optical devices (like FLC EOASLM) due to the need of a nonlocal nonlinearity (the output of each unit in an array depends on a nonlinear fashion on the inputs of all the units in the array). The emerging very-large-scale integrated circuit/liquid crystals (VLSI/LC) device technology enables the design of devices with optical inputs and outputs that can be coupled with almost any desired electronic functionality. A noteworthy illustration of such an implementation has been proposed by Slagter and Wagner in [52], coupling FLC material with photoaddressable silicon VLSI array. Figure 10 shows a schematic cross-section of two units in a one-dimensional VLSI/FLC WTA array.

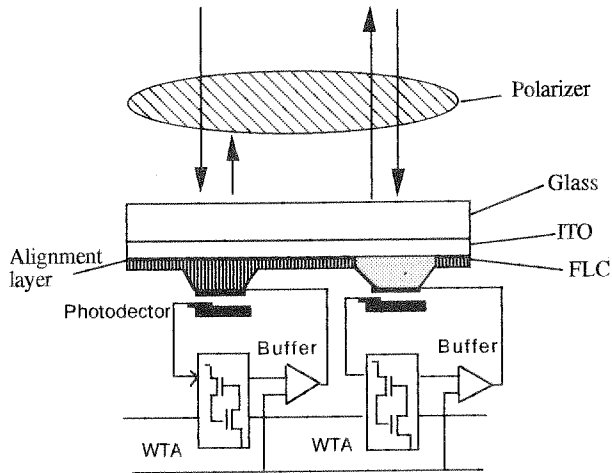


Fig. 10. — Cross-sectional diagram of two units of a VLSI/FLC Winner Take All device (Ref. [49]).

6. Material and device trends.

Liquid crystal light valves still remain the crucial element for many optical information processing, communication, and display systems. Progress in the development of light valves, in particular for optical processing applications, has accelerated in the last few years. We also observe the penetration of such SLM technologies into new applications, namely, those of phase conjugation, adaptive optics, and neural network systems. The implementation of real time correlators using fast light valves and SLMs is now a reality. This is due to the arrival of new devices on the market, with better performances and reliability. Therefore, the implementations have overcome the level of the bench prototype and concern now the domain of industrial applications. Advances in the field of optical light valve design have been decisive and contribute directly to the elaboration of a new kind of optical hardware.

We believe that the real challenge lies in our ability to design complex versatile devices such as smart light valves and, more generally, devices coupling electronic and optical functions on a large interconnectable array. It is expected that smart light valves will be the key components of future data processing systems because they can blend the functional flexibility of electronics and the communications and interconnections capabilities of optics. Therefore, we can foresee applications of silicon VLSI/smectic A or C* optoelectronic devices in areas where massive parallelism and a low power operation at moderate speeds may be suitable, such as special purpose image processing systems, realization of early vision models and optoelectronic neural network. Silicon VLSI/FLC light valves have the great advantage of simplicity of design and fabrication, simplicity of integration with standard electronics, low power requirements, relatively inexpensive fabrication, high frame rates, and the possibility of fabricating large two-dimensional arrays. In this prospect, new generations of light valves based on this principle will bring considerable changes in the field of image processing in the next few years, if we are able to design devices with a satisfying optical quality.

Furthermore, SLMS have suffered both a moderate speed and contrast reduction due to alignment defaults (particularly true with FLC materials). Developments of new materials such as fast smectic A and antiferroelectric liquid crystals (AFLC) [53], with better optical quality than FLCs (i.e. high contrast, less zig-zag defects, etc.) will considerably improve the performances of smectic A and C* LCLVs. Particularly, the use of AFLC will reduce

considerably the technological constraints. Tri-stable switching shows a double hysteresis loop, satisfying the multiplex driving specification. Moreover, since in the AF state the polarization charges cancel between layers, the « ghost » phenomenon can be avoided. For this reason, the tri-stable switching will argue in favour of strong developments of smart light valves involving low power and high contrast liquid crystal material in the near future. Regarding the problem of the photoaddressing, the development of new photoconductive materials such as a-Ge:H, a-Ge_xSi_{1-x}:H alloys [54], a-Si_{1-x}N_x:H [55], a-Si_{1-x}C_x:H, their devices and the related technology matched with smart valves will certainly spread application areas of the light valves.

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