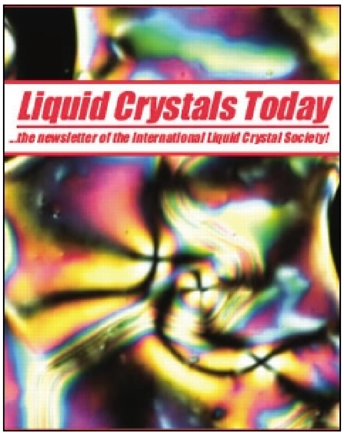

# Liquid Crystals Today

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# NEW APPLICATIONS FOR FERROELECTRIC LIQUID CRYSTALS

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*Newsletter of the International Liquid Crystal Society*

LIQUID CRYSTALS *Today*

*Vol. 4, No 3, December 1994*

## A New Beginning for *Liquid Crystals Today*

Following discussions and negotiations over the past few months, the Board of Directors have agreed to transfer the publication of *Liquid Crystals Today* to publishers Taylor and Francis Ltd. The transfer is expected to take place early in 1995, and the first edition of the new *Liquid Crystals Today* is scheduled to appear in March 1995. Members of the ILCS will continue to receive their copies free, but publication costs will no longer be borne by the Society. The savings generated will enable the Society to develop new initiatives for the benefit of its members. *Liquid Crystals Today* will continue to be the official publication of the ILCS, but it is intended to expand its contents and coverage. The ILCS are in the process of establishing an Editorial Board, which will be responsible for the content of Liquid Crystals Today, and will guide the development of the Newsletter to serve the interests of members and liquid crystal scientists around the world.

Liquid crystal displays are now regarded as mature technology, but as this issue's feature article indicates, there are many other exciting possibilities to be exploited. There are also many remaining challenges in the basic science of liquid crystals, and *Liquid Crystals Today* will attempt to provide the interface between basic science and new applications. It is hoped that all those involved in liquid crystals will welcome the opportunities provided by the new *Liquid Crystals Today*, and will continue to support it.

*David Dunmur, Editor*

### *CONTENTS*:

# *NEW APPLICATIONS FOR FERROELECTRIC LIQUID CRYSTALS*

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### Ferroelectric Liquid Crystal Spatial Light Modulators

The evolution of Ferroelectric Liquid Crystal (FLC) Spatial Light Modulators (SLM) has heralded a new era in optical computing. The FLC properties permit a wide range of non-display applications to be implemented, e.g. optical correlation with the Binary Phase Only Matched Filter (BPOMF), Computer Generated Holograms (CGH), and a variety of optical switching applications and optical neural networks. The development of VLSI (Very Large Scale Integration) backplane SLMs [1] allows architectures to be directly translated to exploitable commercial applications.

The FLC SLM can modulate the phase or intensity of light using the characteristic optical properties of the LC pixels. The liquid crystals used in FLC devices are in the chiral smectic C (tilted) phase, and when confined in a thin cell (several microns thick) the orientation direction of the liquid crystals (the director) is restricted to two allowed states, one of which is selected by appropriate alignment layers. Under these conditions the liquid crystal is a uniform optically uniaxial layer, and as there is a dipole moment associated with the liquid crystals, they can be switched electrically from one allowed state to the other. Applying a field across the FLC cell causes the molecules to 'flip' into their lowest energy state; reversing the field will select the other state. This is equivalent to rotating the optic axis through twice the tilt angle (2θ), and this rotation can be used to create amplitude or phase modulation. Figure 1 shows the structure of a single backplane SLM pixel: transparent electrodes are deposited onto the glass, and alignment layers over these. The ferroelectric liquid crystal material is sandwiched between the top electrode and an aluminium mirror deposited onto a silicon wafer; spacers control the FLC layer thickness, and VLSI circuitry controls the voltage across the pixel and decodes signals from the electronic interface.

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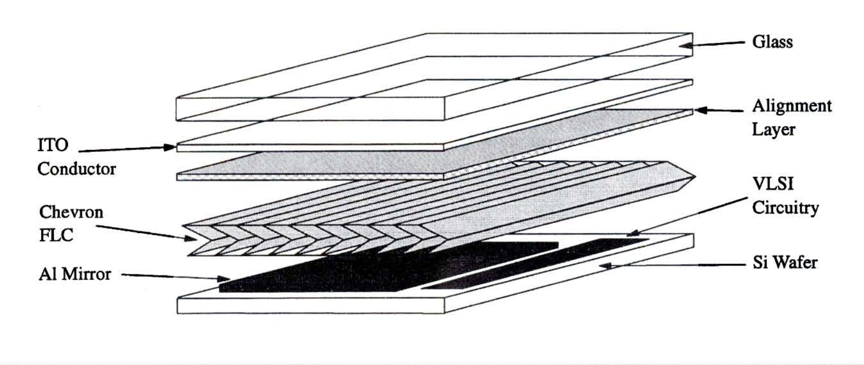

***Figure 1.*** *A single FLC backplane SLM pixel structure*

The dynamics of FLC pixels can be considered in terms of switching between the two possible optical states stabilised by opposite polarity electric fields. The pixel behaves as an optical wave retardation plate, and the modulation of the light depends on the orientation of the axes of the pixel. For pure phase modulation the axes of the two possible states are symmetrically arranged ($\pm\theta$) with respect to incident vertically polarised light. Transmitted light suffers a phase retardation $\alpha$ through the cell, which depends on the refractive indices of the liquid crystal (birefringence), the wavelength of the light and the thickness of the cell. The light is analysed using a polariser set at 90° to the incident polarisation, and the amplitude of the light transmitted for the two switched states of the FLC is the same, but out of phase by 180°. This $\pi$ modulation is independent of the cell parameters $\theta$ and $\alpha$, but there is an associated loss through the pixel. However if $\alpha = \pi$, so the cell thickness is matched to the wavelength, and $\theta = \pi/4$, the cell is loss-less, and polarisers are no longer required to achieve the $\pi$ phase modulation.

Modern FLC materials promise very high switching speeds, and current research is very close to developing an FLC with a $\pi/4$ tilt angle. A current state-of-the-art material can provide switching speeds close to 10 μsec at a voltage of 10V and at a temperature of 45°C (a likely chip operating temperature): this allows frame rates over 5kHz and high pixel densities. Great improvements are possible when the FLCs are combined with silicon backplane VLSI circuitry to construct SLMs. Devices in both Dynamic RAM or Static RAM fabrications have been demonstrated, both having frame rates in excess of 5kHz. The 176x176 DRAM device shown in Figure 2 has a 25 μm pixel pitch and a 60% fill factor.

The mode of operation in these devices is currently binary, but there is no reason why other liquid crystal phases, e.g. the chiral smectic A, cannot be used to achieve a grey-scale modulation [2].

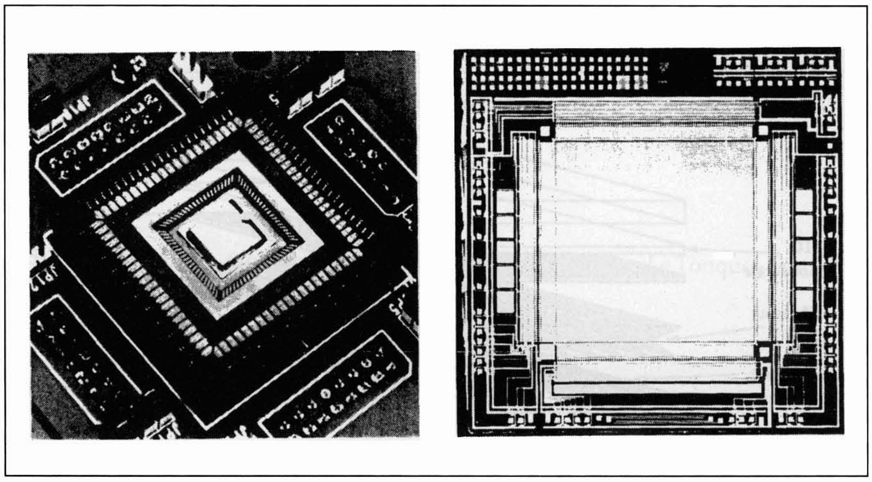

***Figure 2:*** *The 176 x 176 DRAM silicon backplane SLM*

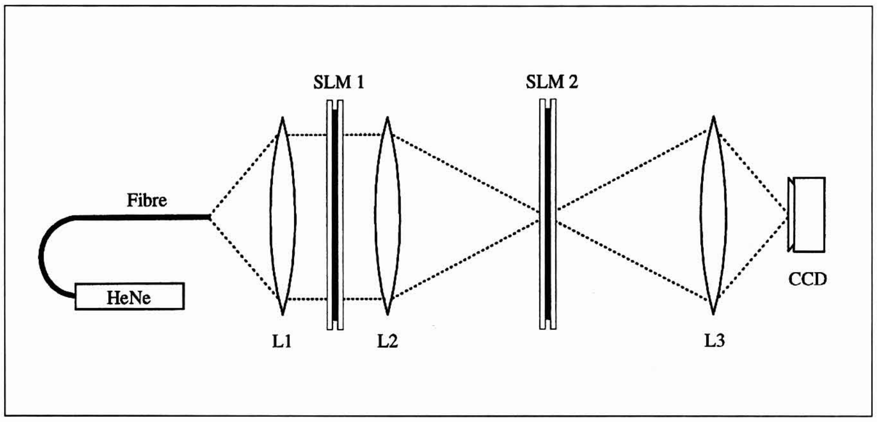

***Figure 3:*** *Classical 4f van der Lugt BPOMF correlator*

Current devices are not of sufficient quality to perform good phase modulation because of the low fill factor and the poor quality of the mirror deposited onto the silicon. A new technique of planarising the die containing the SLM backplanes has proved to be useful in alleviating these problems [3]. This technique improves the flatness of the devices, gives fill factors > 90% and results in higher quality mirrors; the new devices are ideally suited to non-display applications such as the filter SLM in a BPOMF.

## Non Display Applications

**The Matched Filter** — An all-optical correlator architecture was proposed by van der Lugt in the late 60s, which used spatial filtering in the Fourier domain to achieve correlation. Such a technique is directly applicable to SLM technology, as demonstrated by Psaltis [4]. In the matched filter the input and reference images are in separate planes: the input is displayed on an SLM and Fourier transformed to give the spectrum, which is multiplied by passing it through a second SLM containing the matched filter image. Since the filter is based on the Fourier transform of the reference image, transformation of the resultant product gives the correlation output.

Figure 3 shows a typical 4*f* van der Lugt BPOMF correlator: SLM 1 displays the input image, while SLM2 flashes through the filters. The system is illuminated by a single collimated laser, while the lens system between the two SLMs performs the Fourier transform of the input, and also magnifies it to match the pixellation of the filter SLM [5]. Separation of the two SLMs allows different types to be used e.g. a grey-scale device can be used for the input, while an FLC device capable of phase modulation must be used in the filter plane. The input SLM could be a twisted nematic display running at video rates, but the filter SLM is more critical as is contains the reference information. The biggest limitation posed by the SLM technology is the compactness of the BPOMF, and this is directly related to the pitch of the SLM pixels.

**Optical Switching Architectures** — ***The matrix-matrix crossbar:*** An optical vector-matrix processor for fast Fourier transform calculations was first proposed in 1978, and more recently a design for a general matrix-matrix crossbar has been given [6]. This architecture passively 'fans-out' each optical input towards every output (Figure 4), and the replications of the inputs are 'shadowed' by means of a reconfigurable shutter array, which allows selective 'fan-in' at the output array. High-speed electrically-addressed liquid crystal SLMs operating in a binary transmission mode can be used as the shutter plane. Each input replication must be optically resolved through a single shutter, so that any arbitrary interconnection pattern can be formed, including broadcast, multicast and multiple fan-in. Reconfiguration of the switch simply involves closing any (single) shutters corresponding to completed cells, and opening any new paths required. The intrinsic replication of optical inputs leads to a power loss of $N^{-1}$ per input, assuming N-to-N routing. However by imaging the replications onto the shutter plane, very little of the SLM needs to be optically active, allowing control circuitry to be placed around the pixels. A passive diffractive phase plate or hologram is well-suited to performing the fan-out opera-

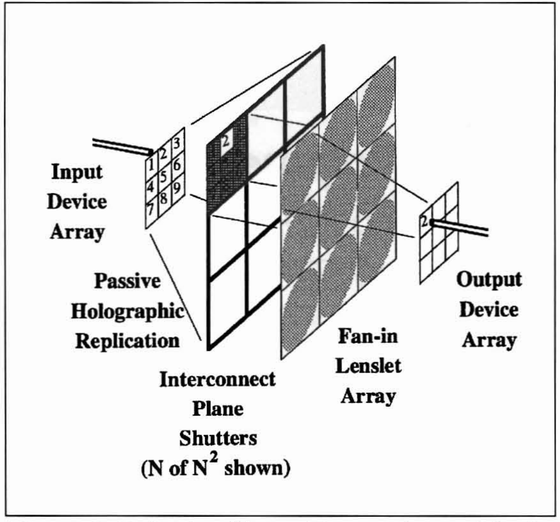

***Figure 4:*** *Optical matrix-matrix crossbar architecture*

tion, while fan-in can be achieved using a multiple lens array, which could also be diffractive. The argument of reciprocity leads to the conclusion that if the input and output devices have the same numerical aperture, there must exist a N$^{-1}$ power loss in addition to the fan-out replication loss. An optically transparent matrix-matrix crossbar with N inputs placed in a single mode fibre network would therefore have a N$^{-2}$ power loss per input, in addition to any other optical losses, and so pre- and post-optical amplification will probably be necessary. The use of high numerical aperture devices such as multi-mode fibres may avoid the fan-in losses.

***The dynamic holographic crossbar —*** The production and use of computer-generated holograms is well-documented [8], and such holograms are usually coarsely-quantized representations of a sampled two dimensional Fourier transform of a desired image. The principle of operation of the holographic crossbar is the use of holograms to deflect as much optical power as possible from the inputs to the outputs, by eliminating the initial fan-out operation associated with generic matrix-matrix architectures [9]. Thus the interconnect plane is divided into N routing areas and each routing area is filled from a set of base holograms which may be stored in a non-volatile memory behind the interconnect plane (Figure 5). Each hologram acts as an independent diffraction grating, and has an associated quantization noise-limited diffraction efficiency, which will generally be less than unity. Input broadcasting or multicasting may be achieved simply by designing a routing hologram to produce more than one output peak. The holograms are spatially invariant, so fan-in from multiple inputs to a single output may also be achieved by placing the same hologram in more than one routing area. An electrically addressed SLM operating in a binary phase mode produces a more efficient system than an amplitude mode device because the zero-order (non-diffracted) path can be eliminated in the output plane by ensuring that there are equal pixel numbers of each phase state. However because of the binary nature of the Fourier plane, both configurations lead to redundant rotational symmetry in the output plane, which can only be removed by using more than two phase levels in the hologram. A key scaling issue of the hologram interconnect is the number of pixels required per routing hologram to provide acceptable noise characteristics. Discrete Fourier transforms have the property that to be able to resolve the N output ports, each routing hologram must contain mN pixels, where $m \geq 2$ because of the binary redundant symmetry.

***Optical Neural Networks using Smart FLC SLMs —*** Through the high connectivity and parallelism of optics in free space, neural networks with optical wiring show many promising advantages, such as high throughput and possible scalability. However it is equally important to have the functionalities of the network components such as neurons and synapses implemented in the hardware. In this way the entire architecture of a neural network can be transferred into a real system: local parallel operations with fast processing and even learning can then be fully realised. It is clear that the combination of optics as interconnects and electronics as functional elements is crucial to the success of a self-sufficient neural network machine. To achieve this, two VLSI/FLC spatial light modulators with smart pixels have been designed specifically for neural network applications.

The concept of smart pixels is that they perform modulation as a function of the incident light, and that they do so independently. Their functionalities are implemented as individual pixel circuitry on the silicon back plane. Since large arrays are usually desired, an important design consideration is to achieve minimum pixel size and complexity: up to about 105 smart pixels are possible in a single device with the available VLSI technology. Ferroelectric liquid crystals offer high contrast ratios (> 200:1) and fast switching (50µsecs), and analogue modulation is available with some electroclinic chiral smectic A phases [2], for which the tilt angle of the optic axis is proportional to the applied voltage. The analogue response shows no hysteresis, and switching over 15° has been demonstrated for some materials; the capacitance of the LC pixel allows storage of information at the pixel for a limited period. These properties enable effective optoelectronic synapses to be implemented, and so makes learning possible within the device itself.

In the first device, Smart Advanced Spatial Light Modulator One (SASLM1), the smart pixels are designed with functions resembling biological somas [10]. They are arranged in an 8x8 array with a pixel pitch of 400µm in both directions: in each pixel there is a phototransistor and an FLC modulator coupled by a local circuit. The circuit sets a threshold for the input photocurrent, and retains the activation signal in a dynamic latch; via a clock, the next neuronal state is made available at the modulator as one of two bistable optical states. Thus the smart pixel array provides an optoelectronic somatic plane consisting of independent electronic cells. Initial tests have been satisfactory, and a system implementation to achieve a bidirectional associative memory is being investigated.

A second device, SASLM2, is designed to act as a synaptic plane capable of on-chip learning. It consists of an array of 64x64 smart pixels which are able to perform as analogue optoelectronic synapses in an optically interconnected network. In each smart pixel there is a liquid crystal modulator, two photodiodes and an independent pixel circuit. The modulator sets the weight of the synapse via the analogue electroclinic effect in the liquid crystal. A delta rule learning algorithm is implemented in the pixel circuit, such that an increment or a decrement will result in the weight according to the difference of the two photocurrents. One of the two photocurrents represents

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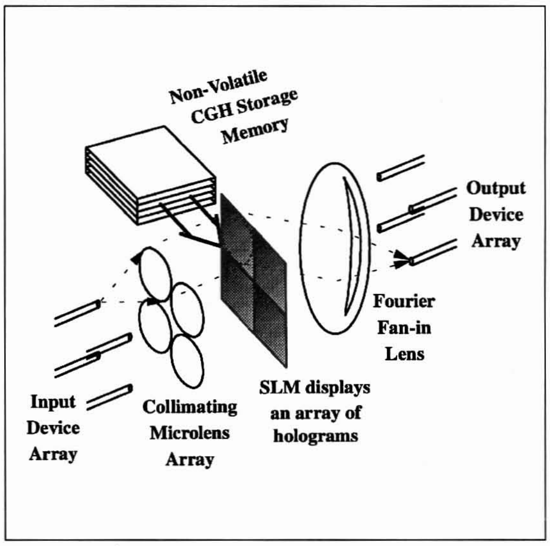

***Figure 5:*** *Optical holographic crossbar architecture*

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an actual neural output, while the other represents a target neural output: repeated presentation of optical patterns then causes the convergence of the weights. Analogue values are retained by the liquid crystal acting as a local storage capacitor with a time constant of ~ 500msecs. When implemented with optical interconnects, the neural network is able to learn by virtue of the SASLM2 synaptic self-modification ability. A system architecture including both SASLM1 and SASLM2 has been outlined, and the backplane layout of SASLM2 is being finalised: it is anticipated that a successful demonstration of liquid crystal-based neural network hardware will be a significant achievement in real-time in-situ learning ability.

***Acknowledgements:***

The authors would like to thank the UK Department of Trade and Industry LINK project "Fast electrooptic effects in chiral smectic liquid crystals" for developing the mixtures used in the devices described in this article. These devices were developed on the UK DTI LINK project "Smart and advanced spatial light modulators" and also on the ESPRIT III project 7050 HICOPOS.

***References:***

[1] N Collings, W A Crossland, P J Ayliffe, D G Vass and I Underwood. "Evolutionary development of advanced liquid crystal spatial light modulators", *Appl. Opt.*, **28**, 4740 (1989)

[2] A B Davey and W A Crossland, "Potential and limitations of the electroclinic effect in device applications", *Ferroelect.*, **114**, 101 (1991)

[3] A O'Hara, J R Hannah, I Underwood, D G Vass and R J Holwill, "Mirror quality and efficiency improvements of reflective spatial light modulators by the use of dielectric coatings and chemical-mechanical polishing", *Appl. Opt.*, **32**, 5549 (1993)

[4] D Psaltis, E G Paek and S S Venkatesh, "Optical image correlation with a binary spatial light modulator", *Opt. Eng.*, **23**, 698 (1984)

[5] T D Wilkinson, D C O'Brien and R J Mears, "Scale invariant binary phase-only matched filter using a ferroelectric liquid crystal spatial light modulator", *Appl. Opt.*, **33**, 4452 (1994)

[6] A G Kirk, W A Crossland and T J Hall, "A compact scalable free-space optical crossbar", *Proc. Third Int. Conf. Holographic Systems*, Edinburgh 1991, 137

[7] W A Crossland, R J Mears, S T Warr and R W A Scarr, "Spatial light modulator based routing switches", *OC' 94, Edinburgh* 1994

[8] D C O'Brien, R J Mears, T D Wilkinson and W A Crossland, "Dynamic holographic interconnects that use ferroelectric liquid crystal spatial light modulators". *Appl. Opt.*, **33**, 2795 (1994)

[9] D C O'Brien, W A Crossland and R J Mears, "A holographically routed optical crossbar: theory and simulation", *Opt. Comp. and Process.*, **1**, 233 (1991)

[10] T C B Yu and R J Mears, "Design and implementation of an associative memory with smart pixels", *J. Intell. Mat. Sys. Struc.*, **5**, 151 (1994).

# *SOCIETY NEWS*

## From the Secretary, Giancarlo Galli

It was an honour for me to be asked to serve as the new Secretary of the ILCS and I fully appreciate how demanding but rewarding this responsibility will be. Since its foundation in 1990, the Society has continued to grow and expand its role in the liquid crystal community and the scientific world at large.

While there are many other organisations of scientists, I believe that the unique aspects of the ILCS are its wide multi-disciplinary character and strong international spirit. The Society is an open forum for over 700 members from more than 40 countries all over the world who have established collaborations and constantly exchange views in research areas with a great deal of innovation. Liquid crystals and the ILCS may have therefore an ever growing significance and impact on both science and technology. The Board of Directors is about to make their choice of venues for the ILCCs of 1998 and 2000: the liquid crystal community is already trying to face the new interests and need of a new millennium. In this context, I like to recall that one of the main objectives of the Society is to establish national societies in different parts of the world. We hope that various national or regional groups

*(continued on page 7)*