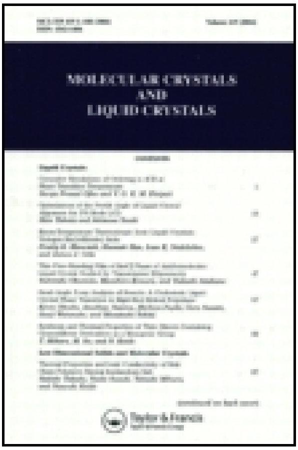

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T. D. Wilkinson [a] , N. New [a] & W. A. Crossland [a]

[a] Cambridge University Engineering, Department Trumpington St, Cambridge, CB2 1PZ

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Optical Comparator Based on an FLC over Silicon SLM

T.D. WILKINSON, N. NEW and W.A. CROSSLAND

Cambridge University Engineering Department Trumpington St, Cambridge CB2 1PZ

Keywords: Optical recogniser; optical correlator; JTC; FLC SLM

Optics provides the potential medium to deal with information at 'the speed of light', hence it is a logical progression from the current electronic state of the art. By exploiting the inherent parallelism of free-space optics, it is possible to design and build optical image processors capable of analysing thousands of two-dimensional images every second. By using ferroelectric liquid crystal (FLC) spatial light modulators (SLMs) as two dimensional light modulation devices, it is possible to build either a binary phase only matched filter (BPOMF)[1] or a joint transform correlator (JTC)[2]. Both architectures exploit the fact that FLCs can be used for binary phase modulation which is independent of both tilt angle and cell thickness and is capable of switching speeds in excess of 10μsec. A further advancement is the development of FLC over silicon VLSI SLMs[3,4], which allow the integration of circuitry with the FLC over mirrors to make an active backplane high speed binary phase modulator with very low pixel pitches. Hence, miniaturisation of the correlator is possible. In the case of the BPOMF, it is possible to make a very compact correlator[5], however it will always be limited by the opto-mechanical system used to make the correlator. This is not such a major issue with the JTC and can be completely eliminated by adopting the binary phase 1/f JTC architecture[6].

Spatial phase modulation

The key concept in an optical image processor is the ability to modulate the light used and dynamically reconfigure a large number of pixels. There are many different techniques available, but one of the most useful discovered to date are liquid crystals, as they offer a large electro-optical effect at low voltages and there are also mechanisms for purely photo-initiated modulation. Liquid crystals have made a huge impact into the field of displays, where the electro-optical effect is used to spatially modulate the intensity of the light with millions of modulators in parallel. More importantly, liquid crystals are capable of spatially modulating the phase of the light, which opens up a vast array of new applications that are currently being researched. Of particular interest are ferroelectric liquid crystals (FLCs) as they have a large electro-optical effect that can be switched in 10μsec and are capable of pure phase modulation. The main limitation is that this modulation is binary.

Electro-optic effects in chiral smectic C phase FLCs.

Molecular ordering and electro-optic switching in chiral smectic liquid crystal phases is discussed in detail in several good textbooks[7]. In the case of ferroelectric switching in chiral smectic C phases, the molecular director n (direction in which the molecule is pointing) is free to move about a cone of angles which is centred on the horizontal axis. Each molecule has a ferro-electric dipole **P**, which is perpendicular to its length. This is demonstrated in Figure 1. When an electric field **E** is applied to the cell, there is an interaction between the **E** and **P**, which forces the director to move around the cone to a point of equilibrium. If the FLC is constrained in a thin layer (usually 1 to 3 microns) between suitable aligning surfaces the cone is suppressed and the precessing of the n director is suppressed to two states[8]. In this case applying an electric field will switch the n director (and therefore the optical axis) from one side of the cone to the other. The angle between the two switched states is the switching angle *θ*, which is twice the liquid crystal tilt angle.

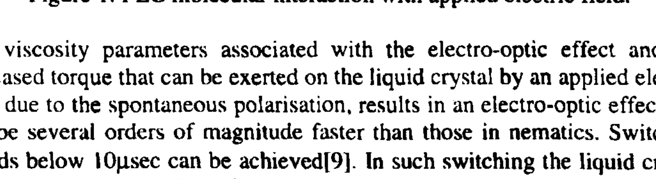

Figure 1. FLC molecular interaction with applied electric field.

The viscosity parameters associated with the electro-optic effect and the increased torque that can be exerted on the liquid crystal by an applied electric field due to the spontaneous polarisation, results in an electro-optic effect that can be several orders of magnitude faster than those in nematics. Switching speeds below 10μsec can be achieved[9]. In such switching the liquid crystal layer acts as an optically uniaxial medium with its optic axis in the plane of the layer. Hence, it behaves like a switchable waveplate whose fast and slow axes can be in two possible states separated by the switching angle *θ* and whose retardation Γ depends on the thickness and birefringence of the FLC. This is not only true for ferroelectric switching in the chiral smectic C phase, but also for electroclinic switching in chiral smectic A phases and for the deformed helix effect in tight pitch helical smectic C structures

The FLC spatial light modulator

A FLC SLM is constructed as a thin layer (around 2μm) of Smectic C^* FLC sandwiched between two transparent electrode arrays. The FLC molecules are aligned parallel to the electrodes by alignment layers. The electric field is applied via a pixellated pattern of ITO (Indium Tin Oxide) on the glass. The rear glass wall can be replaced by a silicon VLSI die to make a silicon backplane SLM. The SLM is now a reflective modulator with the aluminium from the metal 2 of the VLSI process acting as a mirror[3,4]. Circuitry on the backplane can be used to address the FLC pixels as either a dynamic random access (DRAM) pixel[3,4] or as static RAM (SRAM)[10].

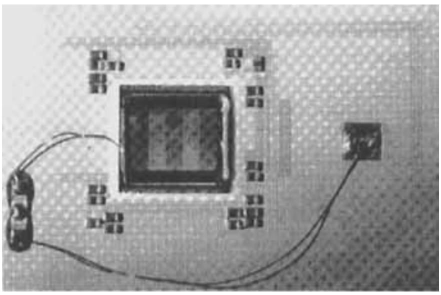

Figure 2 A 320x240 pixel silicon backplane FLC SLM.

The silicon backplane SLM is very important to the development of non-display applications as it allows large arrays of very small pixels to be built on a silicon wafer capable of high-speed addressing speeds. Compared with line-at-a-time multiplexed SLMs, these silicon backplane SLMs allow a full frame of pixels to be addressed in one liquid crystal response period (as opposed to one row), hence they can be K times faster, where K is the number of rows. A 320x240 array of 37μm pixels capable of displaying 44,000 frames per second is shown in Figure 2[11].

Binary Phase Modulation

We can use Jones matrices to model the in birefringence of the FLC layer and we can use polarisors to orient the light and analyse the light after propagation through the FLC If the light is polarised so that its direction bisects the switching angle of the FLC and an analyser (polarisor) is placed after the pixel at 90° to the input light, then phase modulation is possible[12], as shown in Figure 3. If we start with vertically polarised light, then the FLC pixel fast axis positions must bisect the vertical axis and will be oriented at angles of $\theta/2$ and $-\theta/2$ respectively for each state.

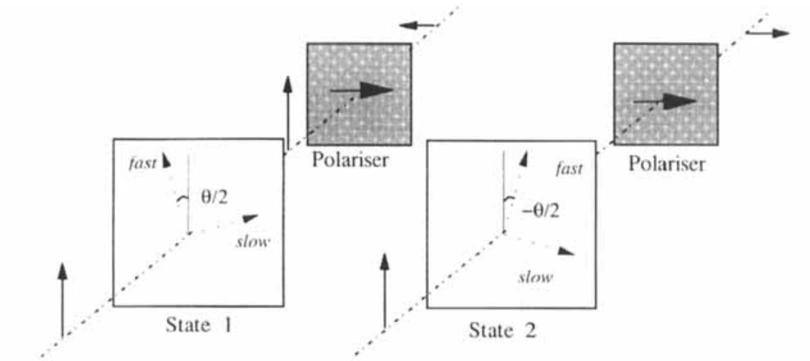

Figure 3 The two states of the FLC for phase modulation.

State 1.

$$\begin{pmatrix} V_x' \\ V_y' \end{pmatrix} = \begin{pmatrix} -V_y j \sin\frac{\Gamma}{2} \sin(\theta) \\ 0 \end{pmatrix}$$

State 2

$$\begin{pmatrix} V_x' \\ V_y' \end{pmatrix} = \begin{pmatrix} V_y j \sin\frac{\Gamma}{2} \sin(\theta) \\ 0 \end{pmatrix}$$

From these two expressions we can see that the difference between the two states is just the minus sign, which means that the light has been modulated by 180° (π phase modulation). Moreover, the phase modulation is independent of the switching angle θ and the retardation Γ. These parameters only effect the loss in transmission through the pixel T. Hence, maximum transmission (hence minimum loss) for phase modulation occurs when $\Gamma = \pi$ and $\theta = \pi/2$.

$$T = V_y^2 \sin^2(\theta) \sin^2\left(\frac{\Gamma}{2}\right)$$

Optical Comparators and correlators

Image processing, compression and pattern recognition are all well established applications for electronic systems, but achieving the high levels of parallelism necessary to do these tasks at high resolution and in real time may be beyond a cost effective implementation in electronics. Several architectures have been proposed for performing these tasks using optics; in particular, the matched filter, the joint transform correlator and neural nets. Once again the key technology is optical modulation and in particular phase modulation. By using modern liquid crystal phase only modulators it is now possible to build image processing systems that greatly exceed the capacity of their electronic equivalents. Such systems all exploit the truly parallel nature of light that allows optical beams to pass through one another without interference.

A very effective method of performing optical correlation is the 1/f joint transform correlator (JTC)[13]. In this architecture there is only one SLM and the input and reference images are displayed side by side upon it. The input image then undergoes a Fourier transform (FT) to form the joint power spectrum (JPS). The JPS passes through a non-linearity before the final FT to form the correlations. The quality of the correlation can be improved by increasing the non-linear processing of the JPS. Recent developments have shown that it is possible to create an optical JTC, or recogniser, based on a single ferroelectric liquid crystal spatial light modulator technology[6]. An efficient JTC can be implemented with FLC SLMs, if the 1/f or two pass architecture is used as shown in Figure 4.

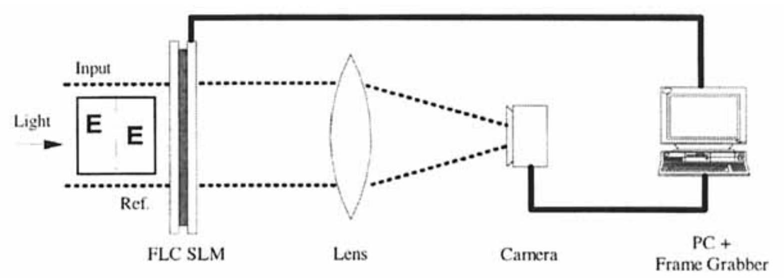

Figure 4. Schematic of the binary phase-only 1/f JTC

The input and reference images are displayed side by side on a FLC SLM. The SLM is illuminated by a collimated laser beam and the images are Fourier transformed by a single lens in its focal plane to form the JPS. The JPS is then imaged onto a CCD camera. The JPS is then non-linearly processed before being displayed onto the SLM again to form the correlation plane. The 1/f JTC is a two-pass system, using the same lens to perform both Fourier transforms and the same SLM to display both the input and the processed JPS. The quality of the correlation peaks and the zero order can be improved by increasing the non-linearity processing acting on the JPS. A binarised JPS produces good sharp correlation peaks and reduced zero order. If the binarised JPS is converted to binary phase modulation [-1,+1], then the zero order can be reduced to around the height of the correlation peaks[6].

An initial experiment was performed to test the binary phase 1/f JTC by displaying two letter Es side by side as the input and reference. The JPS was then taken from the camera as a 320x240 pixel image and processed by the frame grabber. The scheme used to binarise the spectrum was based on a nearest neighbour average comparison, which is a form of edge enhancement. The pixel to be binarised, P_{jk} is thresholded based on the average of its four nearest neighbours above, below and either side.

$$P_{j,k} = \begin{cases} +1 & \text{if} \quad P_{j,k} \geq \frac{1}{4}\left(P_{j-1,k} + P_{j+1,k} + P_{j,k-1} + P_{j,k+1}\right) \\ -1 & \text{Otherwise} \end{cases}$$

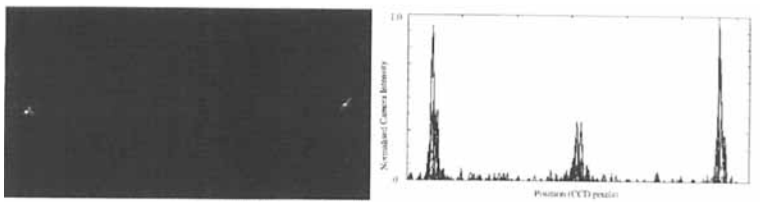

Figure 5. Correlation plane results for an **E E** input plane.

The resulting binarised spectrum is then sent to the SLM for the second pass and the final correlation plane is caught by the CCD camera. The result of using binary phase modulation and the edge enhancing non-linearity is that the zero order is reduced to below the correlation terms, which means it is no longer the dominant feature in the output plane. This can be seen in the output plane of Figure 5. There is also the advantage that the non-linearity can be characterised to suit the exact application intended for the correlator or recogniser. Recent work has developed an in-house SLM based on FLC over silicon technology, the fast bitplane SLM (FBP-SLM)[11]. The FBP-SLM is shown in Figure 2 in its early development stages. The much smaller pixel pitch of the FBP-SLM compared to the transmissive devices used previously, allows a much more compact optical system to be built. Figure 6 shows a basic optical schematic for a 1/f correlator made with the FBP-SLM.

The fast detector array in Figure 6 is currently a standard CCD camera, with two possible options in the near future. The first is a much faster CMOS array whilst the second is a custom designed silicon VLSI smart detector array. The basic unit has been tested as a bench based compact system using similar mounts as the previous system. The overall footprint was 200x200mm, most of which was due to the optical mounts for the components. The control/processor section was done with a standard 200MHz K6 PC containing an inexpensive Epix SV4 PCI frame grabber. The images grabbed from the CCD camera are sent directly via the PCI bus to memory before a Visual C++ program processes the data and sends it via the PC parallel port to the FBP-SLM. The system is currently limited in speed by the CCD camera to around 40 frames per second.

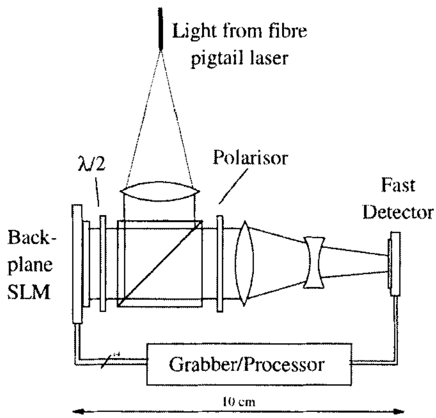

Figure 6. Schematic layout of the compact recogniser.

Initial tests were done with simple images as can be seen in Figure 7, which shows the input scene and the output plane from the system.

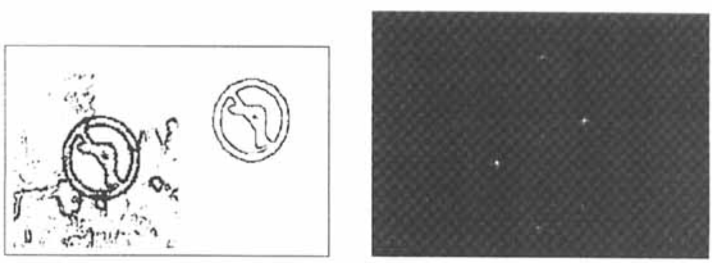

Figure 7. Testing the FBP-SLM correlator; Input image and output plane.

The compact optical comparator using an FLC SLM.

One of the most significant realisations made during the research so far, is that the traditional 1/f JTC can be used as a 'recogniser' or comparator, where the reference image is unknown or unspecified. This completely reverses the role of the correlator and opens up a whole plethora of applications that revolve around object tracking and motion analysis. Rather than having a pre-defined target or reference image, the input is made up from a sequence of frames from a video source. One elegant scenario is when a correlator is used to compare sequential frames in a video stream a production line. In such an application, the current frame is the unknown and the previous frame is the 'reference'. Events that occur from frame to frame can now easily be tracked. This is outlined in the simple yet very powerful example of Figure 8.

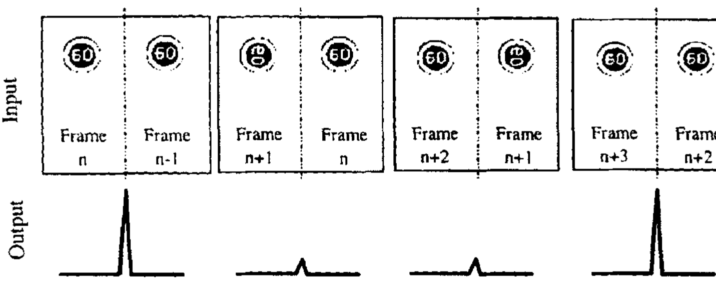

Figure 8. Example application for an optical recogniser.

Here we are implementing an industrial inspection system. The current frame and previous frame are synchronised with the progress of objects through the system (in this example, roadsigns). If the sequence does not change, then the output correlations remain from frame to frame, however, when a change occurs (in this example a rotated roadsign), then the correlation between frames is interrupted. Moreover, the cycle of distortion can be detected by looking at the sequence of disturbances about the first detected defect. Even gradual distortions in the object can be picked up by correlating over multiples of frames to look for small changes. Most importantly, the whole process is done without ever knowing anything about the object being inspected. This application is being tested experimentally as part of an investigation into applications and markets of this technology. One area that is being tested in the inspection of labels on a production line. The issue here is to detect missing or distorted letters in the names printed onto labels in a production process. An example of this can be seen in Figure 9, with both input and output planes from a test sequence shown.

Figure 9. Input and output planes for the optical recogniser inspecting a label that matches and a label with defect.

The recogniser easily detected the label with the missing letter, with a 6.1dB difference between the respective correlation peaks. These results show how a powerful inspection system can be built with the recogniser. The sensitivity can be enhanced by fine tuning the spatial frequencies that are edge enhanced after the first pass through the system, providing a means of tailoring the recogniser to specific object structures and applications.

Current research is being conducted into how very small differences between objects may be amplified within the JTC, in order to increase the overall sensitivity of the system. The intended application for this is centred around the dot matrix "Best Before Dates" printed on everyday foodstuff products. Very small errors being made in the printing, such as the centre line in an "8" could lead to the code being misinterpreted as a "0". The correlator system therefore needs to be highly sensitive to small changes. A drop in power of 3dB or greater in the correlation peak intensity is usually thought of as sufficient to be detected. These results have been achieved by examining how pre-processing the input plane and processing the JPS (at the end of the first pass of the system), can affect the intensity peaks in the correlation plane. The results in Figure 10 below, show how the correlation results may be enhanced by employing an erosion technique[14] to the input plane, in conjunction with the edge-enhancement processing to the JPS, as mentioned earlier.

Figure 10(a) shows the input plane, displaying the test object alongside the reference object. Two input sequences were tested on the comparator. Firstly, the standard technique described above was employed, with an autocorrelation (between the upper image in Figure 10(a) and itself) process being performed first. The drop in intensity (in dB) could then be calculated for the cross correlation test (between the upper and lower images). The process was then repeated using erosion on the input plane images. The results in Figure 10(b) & (c) show a drop of 1.85dB for the standard technique and a substantial drop of 6.71dB for the new one.

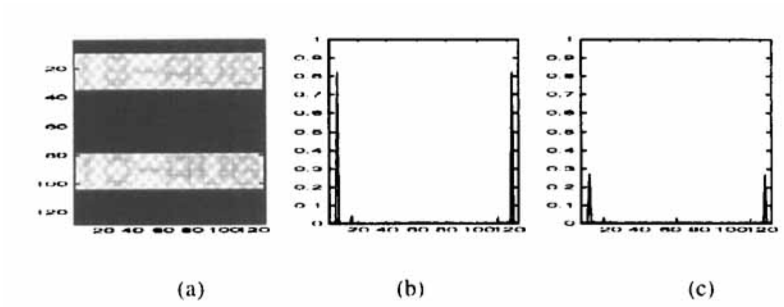

Figure 10. Comparison of correlation tests between a valid label and an invalid label with a slight defect, using (b), the standard technique and (c), with additional pre-processing of the input plane.

Discussion

The application outlined here has demonstrated the use of liquid crystal devices in a non-display system. This is very important as liquid crystals have always been perceived as the mainstay of the flat panel display industry. What is important is the use of phase modulation instead of intensity to implement this application. This is currently limited to binary phase from FLC over silicon devices, but there is great hope in the near future for multi-level phase modulators based on other suitable fast electro-optic liquid crystal effects. The compact correlator or comparator presented here has proven successful at performing complex image processing tasks like industrial inspection that differ from the traditional 'tank-in-the-grass' scenario used to judge optical correlators in the past. There is considerable interest in these systems from many different industrial sectors from mass production houses to public transport and facility security firms. There is a strong need for a system that is capable of picking out undefined defects in undefined objects at frames rates in excess of 1kHz and there is also a need for systems that are capable of tracking objects from one frame to the next in video sequences. The system and modulator we have presented here can perform these tasks and is well on the way to being built as a first prototype.

Acknowledgements

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