Phase modulation with the next generation of liquid crystal over silicon technology

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Received 15th February 2006, Accepted 7th June 2006
First published as an Advance Article on the web 30th June 2006
DOI: 10.1039/b602296k

Liquid crystal materials are fast becoming the *de facto* standard in modern commercial display technology and large amounts of research and development have gone into optimising the materials used in these many types of display. One of the most exciting technologies based on liquid crystal materials is the combination of their optical modulation characteristics with the power and compactness of a silicon VLSI backplane. The next generation of applications for liquid crystal over silicon technology are already starting to emerge in laboratories, however there are severe limitations as the liquid crystal materials have all been optimised for amplitude or intensity modulation when in fact the ability to modulate the phase of the light is more desirable. One example of such an application is adaptive optical interconnects. Data transmission within and between printed circuit boards is becoming more and more important as the data rates in electronic systems increase into the GHz region. One way of avoiding potential data bottlenecks in board to board interconnects is to use optical links to transmit the data. Recent research into free-space optical links has shown that a high level of manufacturing tolerance must be used to maintain the link, however, this can be avoided by incorporating a liquid crystal phase hologram as a beam steering element to compensate for movement between the boards and maintain the optical data path.

Liquid crystal over silicon

The original liquid crystal over silicon (LCOS) devices[1,2] were originally marketed as spatial light modulators (SLMs) and were designed for optical correlators and neural networks. These SLMs initially used the liquid crystal material as a purely intensity modulator or shutter, however the same material can be used in a phase modulation mode, retarding one pixel with respect to another to allow more complex functions to be created. A typical LCOS SLM device structure is shown in Fig. 1. The power of this technology stems from the use of a standard foundry silicon very large scale integration (VLSI) process to create a silicon backplane which contains both pixels and addressing circuitry. The silicon chip (or backplane) can be used to perform the electronic addressing and interfacing to the pixels as well as using the VLSI aluminium to form both the optical and electronic interface with the liquid crystal layer. The device is used in reflection mode with the aluminium pixels on the silicon chip acting as both an electrode with which to apply an electric field across the liquid crystal as well as a mirror to allow optical interaction with the liquid crystal material.

The development of both the technology and the marketing of these devices has now coined the term 'microdisplay' and the SLM of old has become a display light engine component.

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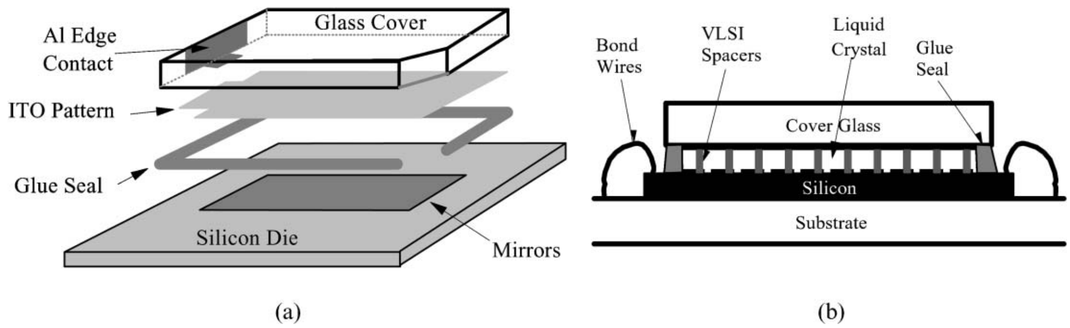

Fig. 1 A typical LCOS SLM construction (from ref. 3). (a) An exploded view of the construction elements and (b) a side profile of the device.

The development of the microdisplay has meant that while the applications of older SLM technology have become more display oriented, the technology behind them has become considerably more advanced and much cheaper through mass production. The SLM represented in the schematic of Fig. 1 originally had a resolution of 320 × 240 pixels and was fabricated using a 2 μm complementary metal oxide semiconductor (CMOS) process using metal 2 aluminium for the pixel mirrors with a 65% fill factor.[3] The modern generation of microdisplay devices have resolutions of 1280 × 1024 (or even 1900 × 1200 for high definition TV) and use 0.5 and 0.3 μm CMOS processes with up to 6 metal layers, multi-level planarisation and cold evaporated top metal for high reflectivity. The mirrors now reside on top of the planarised silicon backplane and have fill factors in excess of 90% with superb mirror quality.

There are many different modulation schemes which can be achieved using liquid crystal materials based on several different electro-optical effects and material properties. The most common two are the ferroelectric liquid crystal (FLC) based on the chiral smectic C phase and nematics. Both types of materials exploit the shape anisotropy of the calamitic liquid crystal molecules to create birefringence to implement the modulation. This is often in conjunction with external optical polarising components such as beam splitters and polarisers. A light wave passing through a liquid crystal material will see different refractive indices depending on the molecular orientation relative to the electric field component and direction of propagation. The orientation of this refractive index relates to the long and short axes of the liquid crystal molecules and this difference in refractive indices (ordinary n_o and extraordinary n_e) leads to a retardation Γ of the wave as it passes through a layer of liquid crystal material of thickness d at a given wavelength λ such that:

$$\Gamma = \frac{2\pi d(n_e - n_o)}{\lambda}$$

The type of modulation achieved will depend on the way in which this property is exploited. In the case of most intensity based modulation schemes used in liquid crystal displays and microdisplays, the liquid crystal is sandwiched between polarisers to orient and then select the desired light and dark states required. In the case of surface stabilised FLC materials[4] this modulation is binary due to the restricted motion of the liquid crystal molecules within the device structure. In the case of nematic materials, the modulation can create grayscales and allows an almost continuous variation of intensity. One of the key developments in non-display application of these materials was the realisation that the polarisers could be removed and the liquid crystal used to modulate the phase of the light. This leads to much higher optical efficiencies as all of the photons can now be manipulated within the optical system.

The exact type and quality of modulation depends on the materials parameters of the liquid crystal materials used. If a FLC material is to be used to create a binary phase modulator, then in order to create perfect 0 and π phase states, the FLC must be made into a perfect half waveplate (*via* the correct thickness and birefringence) and the angle between the two switching states of the FLC must be 90 degrees.[5] If such a modulator were to be used to create a binary phase grating

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Table 1 Applications and their benefits from multi-level phase modulation

Application	Benefits of high speed multiphase SLM
Reconfigurable add-drop multiplexer	Increased optical efficiency (low loss), better noise control (low crosstalk), more ports
Optical recogniser	Increased versatility, better image discrimination, improved invariance properties
Adaptive optics	Improved optical efficiency (low loss), improved aberration correction, more channels
Holographic projection	Better light efficiency, improved noise control, full plane asymmetry
Optical tweezers	Full plane asymmetry, higher particle manipulation density

(alternate 0 and π phase states), then the efficiency of that grating would be the perfect 41%.[6] The limitation of the maximum efficiency comes directly from the binary phase nature of the modulation. If multi-level phase modulation (such as quaternary phase (0, $\pi/2$, π, $3\pi/2$)) were used, then the efficiency increases rapidly towards 100%. In most phase modulation applications such as holography or adaptive optics, 8 levels of phase give an efficiency of 91% which is more than adequate. Multilevel phase modulation can in fact be achieved using a nematic material with the correct birefringence and molecular orientation,[7] however these materials are inherently slow (10–100 ms). The restriction of binary phase modulation with FLCs are also tied in with the material's viscosity and electronic properties through its switching speed. Many FLCs can respond in 10–100 μs which makes kHz frame rates possible. The exact choice of modulating device depends on many different parameters such as desired efficiency and frame rate and is often a complex compromise of performance. For this reason, a truly multi-level phase modulating device capable of kHz frame rates is highly desirable.

The latest generation of LCOS devices are now being incorporated into non-display applications such as optical comparators,[8] optical tweezers[9] and optical telecommunications switches.[10] The problem with these devices is that they have been optimised for intensity display at video rates and the majority of non-display applications would like to utilise phase modulation to increase light efficiency and improve non-linear performance. One of the key technological developments for the next generation of LCOS devices is the creation of a high speed multi-level phase modulation device capable of 8 phase levels over a range of 0 to 2π at frame rates in excess of 1 kHz. Such a device will have a dramatic effect on non-display applications such as those highlighted in Table 1.

In many of the applications in Table 1, nematic LCOS devices have demonstrated the benefits of the multi-level phase modulation, but are limited by the slow response time of the nematic LC. This is especially the case in telecommunications applications where the infrared wavelengths further slow down the response times by requiring thicker devices. Hence the main materials challenge for these applications is to find a suitable high-speed LC material with a suitably high birefringence at the desired wavelength. There are several potential liquid crystal material candidates including smectic A, distorted helix, electroclinics and flexoelectrics, however none of these have yet to deliver the full 2π phase depth required in these applications.

As well as improving the LC materials properties, there is also considerable interest in investigating the limits of the silicon backplane itself. This has benefited heavily from the electronics industry's quest for smaller and smaller feature sizes in the VLSI chips used in modern applications. 0.25 μm feature sizes are now commonplace and 0.18 and 0.1 μm form the leading edge of foundry processing. These feature sizes combined with the commercial availability of processes such as planarisation and optical quality metallisation, brought about by the growth of the microdisplay industry, mean that very complex structures can be built at the pixel level. Such devices were originally proposed as 'smart pixels', with 5–10 transistors per pixel, however these have evolved into 'intelligent pixels' with 100s of transistors at every pixel. One such intelligent pixel chip currently in the prototype phase is the multi-media communicator chip,[11,12] which is capable of capturing a QCIF (176 × 144) pixel image and compressing it using wavelets at the pixel level, as well as decompressing and displaying an image with the same set of pixels. The pixel structure of this chip is shown in Fig. 2.

The chip uses highly dense circuitry at each pixel to capture an image and then compress it, encode it and send it at first generation mobile phone data rates. The same pixel can also decode and decompress the image before being displayed on a liquid crystal over a silicon mirror on top of the pixel circuitry.

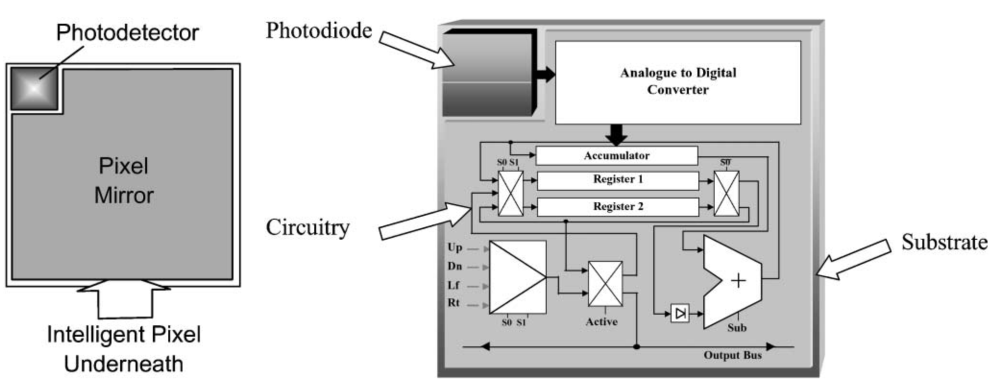

Fig. 2 Top and edge view of the intelligent pixels multimedia communicator chip.

One of the major drawbacks in this process is the fact that as the VLSI foundry feature size drops, so too does the available voltage on the chip to drive the LC material. Hence the search for the ideal multi-level phase modulating material is made even more difficult as it must also respond to a very low voltage (of the order of 1 to 3 V) in order to remain compatible with the VLSI processes. This design conundrum may well result in a compromise with few silicon backplanes being built with features below 0.25 μm.

Adaptive optical interconnects

One of the most fundamental mechanisms of optical propagation is through the process of diffraction. This predicts the passage of an optical wave through a pixellated object such as a hologram or grating. The relationship between a hologram or grating and the pattern which is generated in the far field *via* the process of diffraction is in fact a two dimensional Fourier transform and we can exploit this to control the distribution of optical energy in the far field. Given a desired distribution of light in the far field we can calculate a suitable hologram or grating to generate that pattern. This process is improved considerably when a purely phase only hologram or grating is used to diffract the light as this means that no photons are blocked in the process. In the application of optical interconnects, a beam is propagated from a transmitting laser to a receiving photodetector and as long as the two elements remain aligned, then all of the light will be captured on the detector. If, however, any of the elements in the interconnect move, then there is a chance that the beam will miss the detector leading to a loss of data in the interconnect. By using a hologram or grating to steer the light by diffraction, we can correct for any motion or misalignments and create an adaptive optical interconnect. More over, if there are any aberrations in the optical system which will lead to distortion or blurring of the received beam, then we can add the inverse of these to the hologram and correct for them as well.

Adaptive optical interconnects are one of the most interesting non-display applications of LCOS technology as they do not immediately require the full functionality of the next generation of LCOS devices. In fact, a very powerful adaptive optical interconnect with full aberration correction[13] can be created using an off the shelf FLC LCOS SLM used as a binary phase modulator.[14] Even working at a wavelength of 850 nm has not proven a limitation when using binary phase, however much improved performance would be seen if a fully optimised multi-level phase device were available. The advantages of using a diffractive approach to adaptive optical interconnects includes that there are no moving parts, the long-term stability is better and it is simpler to implement closed loop control than in a mechanical based system. In addition, the deflection angle is a function of hologram pattern only, and thus the beam is deflected to exactly the same point for any given pattern. The discrete nature of an SLM, and fact that it operates in the Fourier plane, make it relatively insensitive to pixel errors, thereby offering the possibility of utilising a modest yield SLM fabrication process. Moreover, it is possible to correct for aberrations in the optical system introduced by both fabrication and alignment errors.

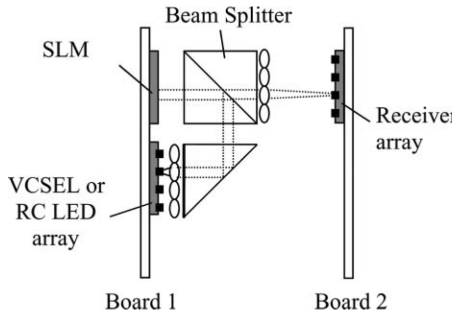

Fig. 3 Adaptive optical interconnect using a hologram displayed on an FLC over silicon SLM. The laser source is a vertical cavity surface emitting laser (VCSEL) or a resonant cavity light emitting diode (RC LED).

A free-space optical interconnect usually consists of two planes, the input plane and the output plane, as shown in Fig. 3. In the input plane (board 1) is an array of lasers, and in the output plane (board 2) an array of photodetectors. Between them, an imaging system is located that consists of optical elements such as lenses, beam splitters, *etc*. In order to simplify the optomechanics of these systems, it is proposed that a liquid crystal SLM displaying a hologram be used. By using a reconfigurable hologram we can steer the beam to any desired positions in the detector plane. The hologram is displayed on a FLC LCOS SLM. A key feature of FLCs is that they have quite high switching speeds (~μs). Another useful characteristic is that they can be made bi-stable and therefore maintain the link uninterrupted if desired.

Suitable adaptive binary holograms can be designed with an optimising algorithm such as direct binary search or simulated annealing. However, these techniques are computationally expensive. In order to achieve active alignment we need to generate holograms in real time and thus use a non-iterative algorithm for hologram design. A second issue is that the SLM must maintain DC balance during the display of each corrective pattern. If a DC field appears across the FLC for more than a few seconds to hours then it will begin to chemically degrade in an irreversible fashion. The simplest way of achieving DC balance is to invert the frame as the inverted frame has the same Fourier transform when using binary phase modulation. However there is a 3 dB glitch in transmission power every time the frame is inverted which is unacceptable for data transmission across the optical link. An elegant solution to this is to use a scrolling scheme to exploit the shift invariant properties of the Fourier transform to gradually DC balance the frame through a series of shifts in the hologram pattern. This scrolling process can be combined with the fact that the hologram for a single port will always be a grating structure of stripes which can be calculated using a modulo 2 quantised 1D phase ramp shifted for each row.[14] This is implemented in digital electronic hardware and the results of this scheme are shown in Fig. 4.

The control of the adaptive optical link is another key issue in its successful operation. The basic function of the tracking system can be modelled as a simple linear system using basic control theory. This works well for single step functions, but is limited on ramp and harmonic disturbances due to the discrete

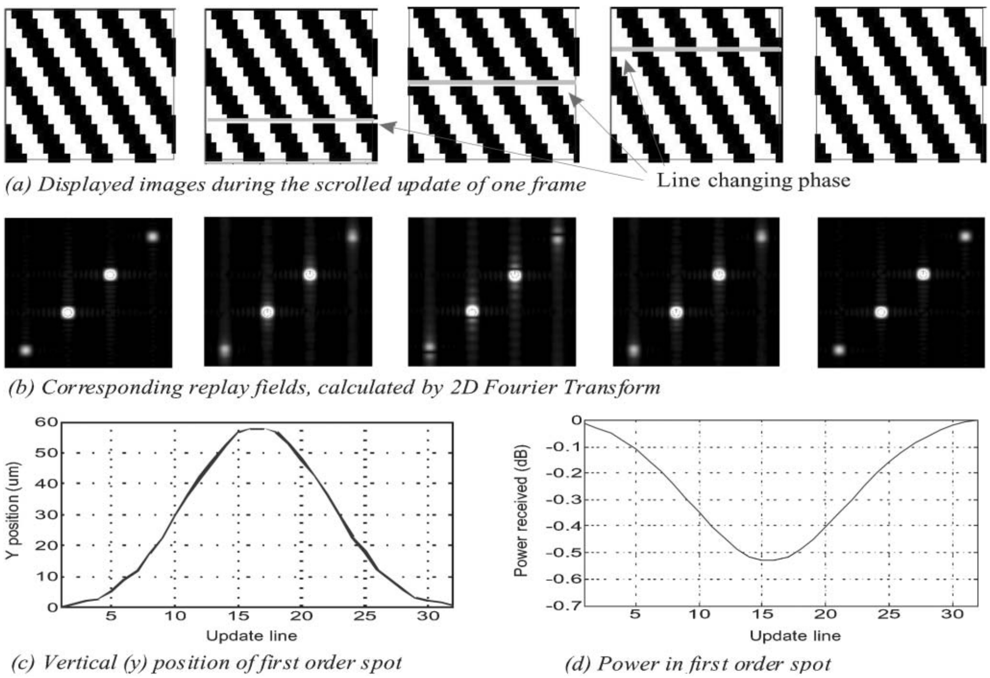

Fig. 4 Scrolled modulo two calculated holograms for DC balancing. (a) The initial hologram followed by the scrolled frames. (b) The hologram replay fields. (c) Shifted offset of the interconnect channel. (d) Ripple of the interconnect channel.

nature of the positions of the spots in the replay field of the hologram. To improve this, more sample points (and therefore hologram replay positions) are needed which either makes the generation of the corrected holograms more difficult or means that a large number of holograms must be stored. Another interesting aspect of this type of adaptive interconnect is that due to the fast hologram generation algorithm used to shift the spot on the photodetector,[14] a simple form of open loop control can be implemented by continuously moving the spot across the detector and monitoring the power level, as is shown in Fig. 4(b). A movement of the detector will upset this pattern and can be detected and corrected without need for a position detector plane.

A simple demonstration system of the adaptive optical interconnect was set up to test the closed loop control algorithms. This did not transmit data as it used a CCD camera to detect the position errors in the spot placement. A collimated 680 nm semiconductor laser diode was used as the light source and a 128 × 128 pixel transmissive FLC SLM with 220 μm pitch pixels was used to display the adaptive optical holograms. A 4f system using 200 mm focal length lenses was used as the interconnect and the final replay field was expanded using a ×10 microscope objective so that it would fit into the CCD camera aperture.

Results from the experimental adaptive optical interconnect demonstrator are shown in Fig. 5 as nine different frames from a real-time video. The box in frame 1 shows where the beam should be targeted to in the adaptive system. The other nine frames show how the holograms have been used on the FLC SLM to compensate for error induced by mis-aligning optical components in the experiment. Each frame in Fig. 5 shows how the beam always returns to the same position on the camera. The adaptive functionality can be seen in the frames by looking at the position of the symmetric orders in each frame.

A second interconnect experiment using real transmitted data at 1.25 Gbit s^{-1} was set up using a 1024 × 768 FLC LCOS SLM from Displaytech. This was driven by a custom electronic interface which combined the addressing of the SLM with the hologram generation and scrolling hardware implemented algorithm as shown in Fig. 4. Fig. 6(a) shows the ripple observed from a photodiode covered by a diffraction order at the receiver plane, for a continuous transmitted beam. Inclusion of the frame sync signal on this trace indicates that, as expected, the ripple period matches the SLM frame rate, and the waveform shape is consistent with Fig. 4(d). The phase and magnitude of the ripple were observed to vary depending on the exact position of the photodiode area over the received order, confirming that it was largely caused by translation of the spot as frames were updated line by line.

With the position adjusted for minimum ripple, the ripple in the first order spot was measured to be 0.2 dB for a grating to place the dot in the middle of the deflection range, increasing to 0.6 dB for a grating giving maximum. Fig. 6(b) shows the received eye diagram when the vertical cavity surface emitting laser (VCSEL) was modulated at 1.25 Gbps. The received optical modulation amplitude was 22 μW, with an input of 0.6 mW. Noise on the waveform is visible due to these relatively low power levels, and is consistent with the random noise expected in the photodiode and amplifier assembly.

Next generation LCOS devices

In order to guarantee the commercial success of these non-display applications of LCOS devices, the next generation are going to have to be capable of multi-level phase modulation

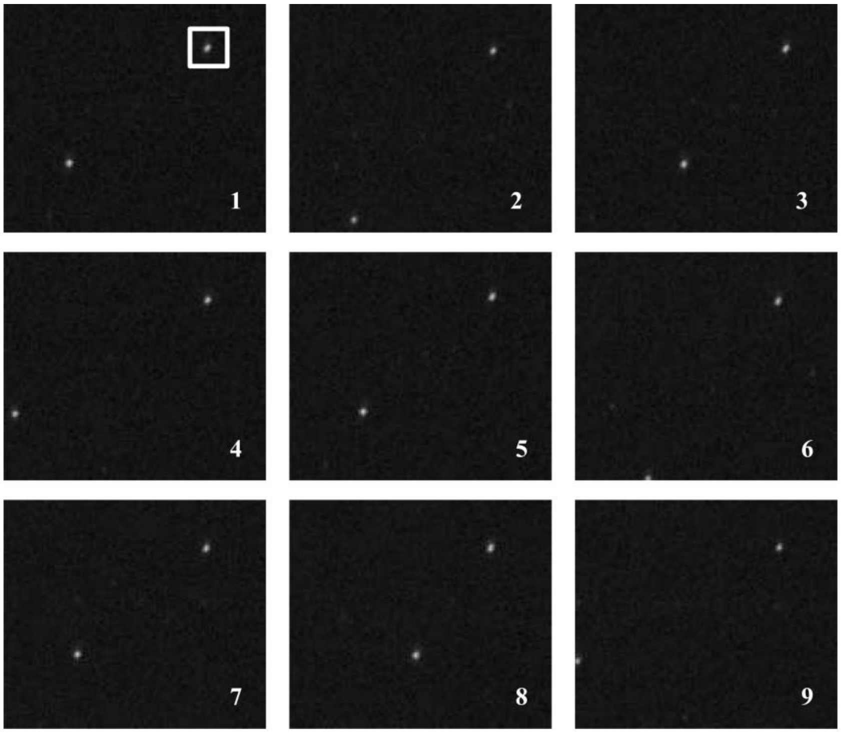

Fig. 5 Experimental output from the adaptive optical interconnect demonstrator. The active channel is shown boxed in frame 1. As the interconnect moves (frames 2–9), the hologram adapts the beam to maintain a constant position. The position of the interconnect can be seen from the location symmetric order in frames 1–9.

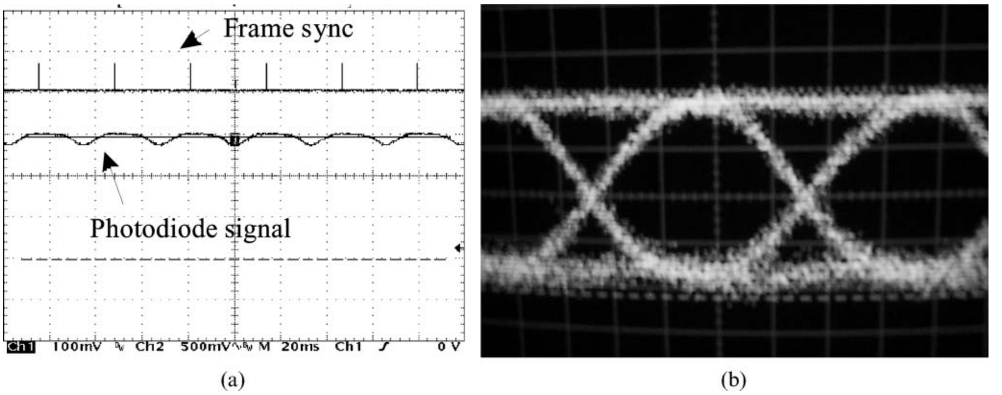

Fig. 6 (a) Observed power ripple in the optical channel. (Vertical scale: 1 μW division^{-1}. The dashed line corresponds to a received power level of zero.) (b) Eye diagram for 1.25 Gbps data.

and ultimately capable of doing so at high frame rates. This has already spawned research into new materials for these applications such as large tilt angle smectic A liquid crystals, blue phase liquid crystals,[15] flexoelectric liquid crystals and chirally doped systems[16] and wide temperature range electroclinics. Applications which use infrared wavelengths also require high birefringence materials to reduce the size of the cell gap in the devices hence work on suitable nematic LC hosts and dopants is in progress. A recent example of a liquid crystal material tried as a multi-level phase modulator was a V-shaped switching material supplied by Mitsubishi Corporation. The diffraction phase results at a 1 kHz frame rate for this material are shown in Fig. 7 and it can clearly be seen that there is multi-level phase modulation, but the phase depth is only π rather than 2π, which limits the usefulness of the material.[17] The result also demonstrated that the effect is polarization dependent, which can be a problem in telecommunications applications.

One of the major unanswered questions in the design of LCOS technology is the choice of alignment agents for the LC materials. The exact aligning properties and correct agents for asymmetric surfaces of glass (ITO) and aluminium (on the silicon) have yet to be discovered as almost all devices in the world today have some issues related to their alignment quality. Undesirable effects such as reverse tilts and defect states have not yet been fully addressed in these devices. Another question to be fully answered is exactly what can be achieved with the latest generations of sub-micron CMOS

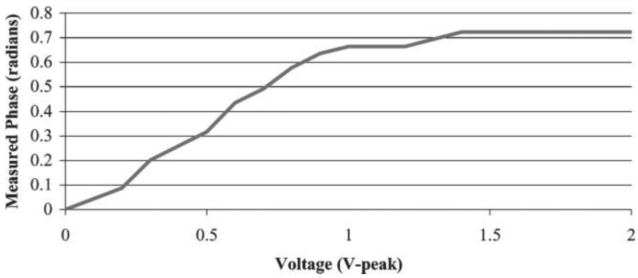

Fig. 7 Phase *vs.* voltage characteristic at 1 kHz for the Mitsubishi V-shaped switching material. 145 degrees linearly polarised input light.

processes. As features sizes get below 0.25 μm, there are many interesting effects which could be exploited in pixel design and LC alignment. The ability to control defect states within the LC material with novel structured pixels and pixel surfaces will become a key advantage of sub-micron CMOS based LCOS devices. Such pixel designs could lead to enhanced modulation states and speed at low voltages by using defects to enhance switching instead of assuming them to be an unwanted feature of the LC alignment. The use of electro-optical effect control *via* novel electrode structures could also lead to new flow based effects such as those used in the world of micro-electrical mechanical systems (MEMS).

The research done so far has demonstrated that we are well on the way to producing a truly hybrid silicon/liquid crystal technology. Devices made so far have ably shown that there is plenty of application and market space for this technology as a form of microdisplay. The most exciting developments have also shown that there are a whole host of 'next generation' applications which will prove even more important than mainstream displays in the future, however we must first solve the key issue of how to implement a truly multi-level phase modulating structure at frame rates in excess of 1 kHz in this technology. There are challenges in terms of both materials chemistry, physics and engineering which must be combined to solve this issue and create the next big break-through in both liquid crystals and their applications.

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.*, 1989, **28**(22), 4840.
2 K. M. Johnson, D. J. McKnight and I. Underwood, Smart spatial light modulator using liquid crystals on silicon, *IEEE J. Quantum Electron.*, 1993, **29**(2), 699.
3 W. A. Crossland, T. D. Wilkinson, T. M. Coker, T. C. B. Yu and M. Stanley, The fast bitplane SLM: A new ferroelectric liquid crystal on silicon spatial light modulator designed for high yield and low cost manufacturability, *OSA Trends Opt. Photonics Ser.*, 1997, **14**, 102–106.
4 N. A. Clark and S. T. Lagerwall, Submicrosecond bistable electro-optic switching in liquid crystals, *Appl. Phys. Lett.*, 1980, **36**, 899–901.
5 M. J. O'Callaghan and M. A. Handschy, Diffractive Ferroelectric Liquid Crystals Shutters for Unpolarised Light, *Opt. Lett.*, 1991, **16**(10).
6 K. L. Tan, S. T. Warr, I. G. Manolis, T. D. Wilkinson, M. M. Redmond, W. A. Crossland, R. T. Mears and B. Robertson, Dynamic holography for optical interconnections. II. Routing holograms with predictable location and intensity of each diffraction order, *J. Opt. Soc. Am. A*, 2001, **18**(1), 205–215.
7 I. G. Manolis, T. D. Wilkinson, M. M. Redmond and W. A. Crossland, Reconfigurable multi-level phase holograms for optical switches, *IEEE Photon. Technol. Lett.*, 2002, **14**(6), 801–803.
8 N. J. New, T. D. Wilkinson and W. A. Crossland, Optimising the discrimination capabilities of the joint transform correlator for a product validation application, *Proc. SPIE–Int. Soc. Opt. Eng.*, 2000, **4043**, 117–128.
9 W. J. Hossack, E. Theofanidou, J. Crain, K. Heggarty and M. Birch, High-speed holographic optical tweezers using a ferroelectric liquid crystal microdisplay, *Opt. Express*, 2003, **11**, 2053–2059.
10 W. A. Crossland, I. G. Manolis, M. M. Redmond, K. L. Tan, T. D. Wilkinson, M. J. Holmes, T. R. Parker, H. H. Chu, J. Croucher, V. A. Handerek, S. T. Warr, B. Robertson, I. G. Bonas, R. Franklin, C. Stace, H. J. White, R. A. Woolley and G. Henshall, Holographic optical switching: The ROSES demonstrator, *J. Lightwave Technol.*, 2000, **18**(12), 1845–1854.
11 A. M. Rassau, K. Eshraghian, H. Cheung, S. W. Lachowicz, T. C. B. Yu, W. A. Crossland and T. D. Wilkinson, Wavelet transform algorithms for smart pixel opto-VLSI implementation, presented at Int. Conf. on Computational Engineering and Systems Applications, Tunisia, April 1998.
12 A. M. Rassau, S. Chae and K. Eshraghian, Simple binary wavelet filters for efficient VLSI implementation, *Electron. Lett.*, 1999, **35**(7), 555–557.
13 D. G. Leyva, B. Robertson, C. J. Henderson and T. D. Wilkinson, Crosstalk analysis in a telecentric adaptive free-space optical relay based on a spatial light modulator, *Appl. Opt.*, Jan. 2006, **45**(1), 63–75.
14 C. J. Henderson, B. Robertson, D. G. Leyva, T. Wilkinson, D. O'Brien and G. Faulkner, Control of a free space adaptive optical interconnect using a Liquid Crystal Spatial Light Modulator for beam steering, *Opt. Eng.*, July 2005, **44**(7), 75401–75408.
15 H. J. Coles and M. N. Pivnenko, Liquid crystal 'blue phases' with a wide temperature range, *Nature*, 2005, **436**, 997–1000.
16 B. J. Broughton, M. J. Clarke, A. E. Blatch and H. J. Coles, Optimized flexoelectric response in a chiral liquid-crystal phase device, *J. Appl. Phys.*, 2005, **98**, 034109.
17 G. M. Long, T. D. Wilkinson and W. A. Crossland, Phase modulation time dependence measurements, *Mol. Cryst. Liq. Cryst.*, 2004, **413**, 2615–2624.