# Polarisation independent phase modulation using a blue phase liquid crystal over silicon device

**Rachel M. Hyman[1,*], Alexander Lorenz[1], Stephen M. Morris[2] and Timothy D. Wilkinson[1]**

[1]*Centre of Molecular Materials for Photonics and Electronics, Department of Engineering, University of Cambridge, 9 JJ Thomson Avenue, Cambridge, CB3 0FA, UK*
[2]*Department of Engineering Science University of Oxford, Parks Road, Oxford, OX1 3PJ, UK*
**Corresponding author: rmh61@cam.ac.uk*

Liquid crystal over silicon (LCoS) spatial light modulator (SLM) technology has become dominant in industries such as pico-projection, which require high quality reflective micro-displays for intensity modulation of light. They are, however, restricted from being used in wider optical applications such as computer-generated holography, adaptive optics, and optical correlation due to their phase modulation ability. The main drawback of these devices is that their modulation is based on simple planar or twisted nematic liquid crystals which are inherently slow mechanisms due to their viscoelastic properties. Their use is also limited due to fact that the phase modulation is dependent on the state of polarisation of the illumination.
In this letter, we demonstrate that a polymer-stabilised blue phase liquid crystal can offer both phase modulation and high speed switching in a silicon backplane device which is independent of the input polarisation state. The LCoS device shows continuous phase modulation of light with a sub-millisecond switching time and insensitivity to the input light polarisation direction. This type of phase modulation opens up a whole new class of applications for LCoS technology.

## 1.Introduction

Spatial light modulators (SLMs) can be used to manipulate the polarisation state, phase, or intensity of incident light, leading to many different applications.[1] In applications such as computer generated holography and optical correlation, continuous phase modulation gives the most optically efficient usage of the light output by removing the 180 ° conjugate image as well as allowing more flexibility in the way the light can be manipulated.[2] For example, in holographic projection displays this allows the full replay region to be used, which is not the case with existing intensity and binary phase modulators. In other applications such as adaptive optics, for full correction, the ability to retard the light through at least one full wavelength is required. For some of the applications, devices with frame rate in excess of 1kHz are very desirable to fully harness the optical functionality.

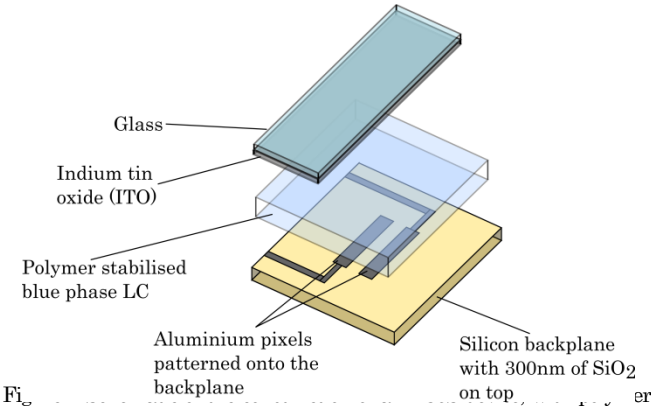
Liquid crystal over silicon (LCoS) devices are a mature technology in the microdisplay market, offering various advantages over other technologies such as micro-mirrors.[1,3–5] The main limitation with LCoS devices to date has been the response time of the liquid crystal, especially if grayscale modulation is required.

The maximum speed and optical efficiency of an LCoS device is mainly determined by the LC switching properties. Ideally, a fast switching, multi-level, full 2π phase modulating material is desired, however, this is not possible using the material properties of currently available LC modes. Full phase modulation is possible by using nematic LCs, but they are slow to switch (10-100 ms) and their phase modulation is dependent on the polarisation of the incident light. Ferroelectrics provide fast switching speeds (10-100 μs), but they only offer binary phase modulation at these speeds. Linear polarisation angle independent devices are achievable but these rely on the use of extra optical components or specific surface alignments, which increase manufacturing costs.[6,7] In a polarisation dependent device, the alignment of the LC's optical axis with that of the direction of the illuminating laser polarisation affects the amount of phase modulation that is observed. There are many applications such as those in telecommunications, where the polarisation of the light is unknown which is a major limitation. The blue phase (BP) electro-optical effects in LCs are potentially fast switching and have the ability to perform multi-level phase modulation. Interferometric phase measurements have been demonstrated but not in silicon backplane reflective devices.[8,9] The BP is a phase of a chiral liquid crystal, usually found over a very narrow temperature range between the isotropic and cholesteric phases. This temperature limitation can be expanded with the use of polymer stabilisation, with BPs recoded over a 60 °C range.[10] A suitable BP LC mixture is doped with a photo-initiator and monomer mixture, which is then UV cured when

the LC is in its BP. This creates a weak functional polymer network in the disclination lattice of the BP LC, stabilising the BP from its clearing point (typically >60 °C) down to room temperature.[11–13]

This method of stabilisation is suitable for two of the three distinctly known BPs, BPI and BPII.[14] Only these two phases are of interest in this research due to their well-defined molecular ordering, unlike BPIII, which is thought to be amorphous.[15] BPI and BPII are three-dimensional cubic structures of double-twist cylinders of chiral nematic creating a lattice of disclinations.[16] They are photonic crystals with a symmetric structure that is optically isotropic when no electric field is applied. There are two electro-optic responses of the these materials, the Kerr effect and electrostriction. The Kerr effect is the induced change the overall material birefringence by the application of an electric field.[17] Electrostriction is the distortion in the crystal lattice by the applied electric field, inducing birefringence.[18] The dominant response in this system is that of the Kerr effect.

A BP can modulate either the intensity or the phase of light with the application of an external electric field.[8,19] In this paper, we present a reflective polymer stabilised blue phase LCoS device, which is used to measure the phase modulation ability of the BP material over several input polarisation states. This material is desirable for use in devices as it is easy to process, operates at room temperature and simplifies manufacturing requirements as an alignment layer is not required.




Fi er stabilised blue phase LC between the two layers

## 2 Experimental Method

The BP mixture developed for this experiment using commercially available materials so the exact composition and properties were known. E7 (Sigma-Aldrich), R5011, EHA and RM257 and the photoinitiator IC819 were used. The mixture composition was (E7 + 4.5 wt% R5011) + 10 wt% reactive mesogen mixture. The reactive-mesogen mixture was (50 wt% RM257 + 50 wt% EHA) + 1 wt% Irgacure819.

The cells designed for the experiment use aluminum pixels on a silicon backplane, emulating LCoS devices. However, they do not have the active addressing systems as they are a proof of principle device. The LCoS cells designed for the experiment, shown in Figure 1, consist of a silicon backplane, and a common indium tin oxide (ITO) electrode on a glass cover. The LCoS cells were made in house by lithographical patterning of two aluminum pixels onto a silicon wafer with 300 nm layer of silicon

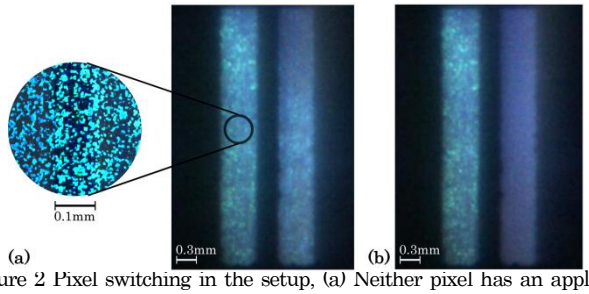



Figure 2 Pixel switching in the setup, (a) Neither pixel has an applied field, with an magnification of the stabilised blue phase. (b) Right pixel with a 20 V $\mu m^{-1}$ field applied, changing its optical properties

dioxide. The top substrate was made from ITO coated glass. The two substrates were glued together using 6 µm spacer bead doped glue. The cell thickness was then measured using the Fabry-Perot interference technique with a spectrometer connected to the microscope (Ocean Optics USB 2000).

The cell gap thickness was measured to be 6.4 ± 0.1 µm over the electrodes. The cell was capillary filled with the BP LC mixture at 70 °C and the BP was observed, through crossed polarisers, at 45 °C as it cooled. The cell was cured using ultraviolet light to polymerise the monomer and therefore lock in the BP texture.[12,20] Ultraviolet exposure of the cell was carried out in stages, checking the alignment between each exposure. The first was at 41.8 °C for 10s, the second for 30s, and the final cure for 3mins. An Omnicure series 1000 spot curing system was used at a light intensity of 10 $Wm^{-2}$. Once fully cured, the BP was stable at room temperature allowing all measurements to be taken at 23 °C. The obtained BP texture can be seen in the inset of Figure 2. It is believed to be BPI but further characterisation is required.

The material properties for this LC mixture were then measured. The 10-90 % response time of the material was measured to be 89µs. This value is typical with other polymer stabilised BP switching times that have been measured.[12,21] The phase measurements were taken at 1 kHz, knowing from the switching time that the material would be fully switched at this frequency.

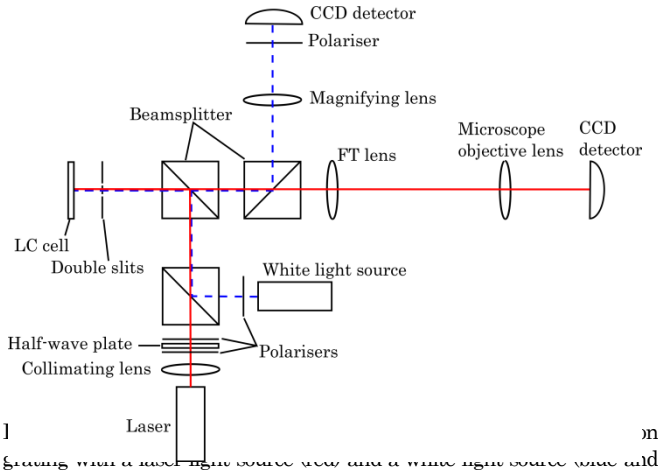
To investigate the phase modulation ability with these cells, the principles of Young's double slit diffraction were used.[22] This technique was chosen over more traditional interferometric techniques as it perfectly matches the diffractive propagation that occurs in both holography and correlation, hence it will give a direct indication of device performance in those applications. This technique allows the relative phase between a non switched and a switched pixel to be investigated as would be the case in a real device. The diffraction pattern of reflected laser light from the two slits (pixels) consists of evenly spaced maxima in the far field. The relative phase of the light between the two pixels corresponds to the position of these maxima. By comparing the relative shift of the central maximum intensity, in a sequence of images at different applied fields, the phase modulation ability of the LC can be measured. When an adjacent maxima aligns with the original position of the tracked maxima, a 2π phase shift has occurred.

The experimental setup is shown in Figure 3. Two optical paths are indicated, one for the path of the laser used for the diffraction measurements, and the other for a white light source to observe the LC texture. The laser wavelength was picked so that it was away from the blue, polarisation-dependent Bragg reflection band.

Collimated laser diode light (652nm) is passed through a polariser before being directed onto the LCoS cell. It is reflected and passed through a lens (75mm) which generates the Fourier transform of the pixels. This diffraction pattern is magnified by a 5x objective lens (Beck, NA 0.12). The image is captured using a camera (Logitech 500) connected to a computer.

A double slit mask is placed on the front of the cell, over the Al pixels to improve the contrast of the maxima in the far field. The slit widths were 0.55 mm with a 0.3 mm separation. This mask also minimises errors in the measurements due to edge field effects and reflections from between the electrodes.

Characterisation of the phase modulation with an applied field was performed in three stages. First, the cell was continuously illuminated with linearly polarised collimated laser light from a 652nm laser diode. A dc balanced square wave (1kHz) was applied to one electrode, creating an electric field between it and the glass plate and thus changing the material birefringence. A sequence of images were recorded with different applied electric fields, waiting 20 seconds between each field change and image capture to make sure that it was in a settled state. A zero applied field image was taken as the reference. The switching of a single electrode can be seen in Figure 2 and a far field image sequence seen in Figure 4 (inset). Secondly, the interference patterns were extracted and peaks were fitted to the centre of the maxima. Finally, the movement of the central maximum between images was calculated, giving the measured phase modulation. The overall results were obtained by averaging over four repetitions of this process.

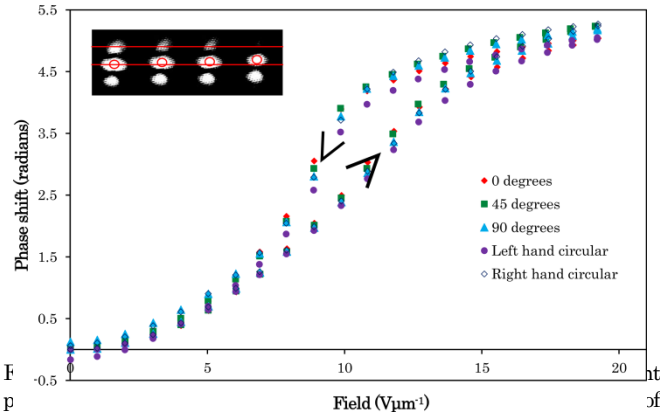



dashed).

## 3 Results

The results obtained for this characterization process of the BP material at different applied fields are shown in Figure 4. The results clearly show that 1.8π phase modulation was achieved with the BP material at an applied field of 20 Vμm$^{-1}$. The response is continuous with applied field. The experiment was repeated with the incident laser light at different polarisations, including both left- and right-hand circular, and the amount of phase modulation observed remains nearly identical. As expected, the electro-optic response only varies slightly with polarisation angle of the incident laser light.

The slight variation observed was mostly due to inhomogeneities in the stabilised blue phase material and the LCoS cell and by residual birefringence of the material. A more




the pixel. The inset shows a recorded image sequence of the maxima diffraction patterns and the associated phase modulation.

optimised BP formation process could be created to minimise these inhomogeneities in the future.

The polymer stabilised BP has hysteresis in its response to the applied field. However, with full characterisation of the hysteresis, including its stability and reliability, it would allow a correction algorithm to be developed for the driving of the pixels so that this effect can be reduced.

Further experiments are needed to determine the response of the material at different wavelengths and a full investigation into the optimisation of the composition of the liquid crystal material used.[23,24] Optimal composition of the polymer mixture for this blue phase and its overall concentration needs to be investigated. Changing the BP mixture to include some bimesogens may help to increase the response, but driving voltages would have to be careful monitored.

This is a proof of principle experiment. If the hysteresis and driving voltage can be lowered to acceptable levels, then it can be tried in devices with a greater pixel density and small pixel pitch (10 μm). It is unknown how the material will behave with the fringe effects between neighboring pixels and this is for further investigation. From these device properties and performances it would then be possible to determine which applications these devices would be suitable for.

## 4 Conclusions

This letter presents evidence of continuous phase modulation in a reflective polymer stabilised blue phase LCoS cell. The electro-optic response is invariant to the polarisation direction of the incident light and showed sub millisecond response times. This investigation shows that the BP is promising material for future LCoS SLM devices in many applications, offering high-speed, polarisation insensitive[6,7] phase modulation. With careful manipulation of the blue phase material composition[23,24] to increase the response, operating temperature, and device thickness, it will be possible to offer full 2π phase modulation in the future, creating an LCoS SLM device with highly desirable properties.

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