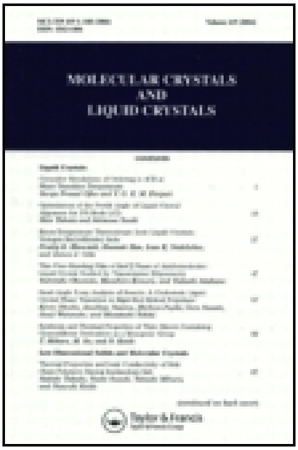

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Modelling of High Resolution Phase Spatial Light Modulators

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MODELLING OF HIGH RESOLUTION PHASE SPATIAL LIGHT MODULATORS

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A programmable LCOS reflective spatial light modulator using an array of liquid crystal pixels used as a phase modulating device is studied. Modelling has been performed to determine the pattern of electrode voltages required to achieve a blazed grating with a linear phase ramp and an abrupt phase transition. As two-dimensional steering of incoming wavefronts is required, oblique gratings are also considered and the effect of the angle of the pixel grid with respect to the phase front of the grating is also considered. Here we study this effect using two possible configurations of the director pre-twist.

1. INTRODUCTION

Spatial light modulators (SLMs) consist of one- or two-dimensional arrays of elements that are used to modulate the intensity and phase of an optical wavefront by an electrical or an optical input. There are many applications, such as projection displays and optical correlators, but here we consider a programmable high-resolution SLM, which is of importance in optical communication systems, where they can provide a means to reconfigure the connectivity of the system. Arrays of liquid crystal (LC) pixels have been used for this purpose [1–6].

Liquid crystals have widely been employed as the display medium for SLMs. The LC medium can be tuned by an electric field in order to

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modulate the incident light by birefringence, polarisation, absorption and scattering. Another benefit is that the liquid crystal can be dynamically adjusted to steer the wavefront in a new direction.

Both transmissive and reflective configurations are possible, but the reflective systems offer advantages in terms of a larger aperture ratio and a more compact system, with a faster response time due to their smaller cell thickness [7]. LCOS (Liquid Crystal on Silicon (LCOS) devices are constructed from a layer of liquid crystal material which overlies a substrate of pixelated mirrors made from a nearly conventional CMOS substrate.

In this paper we consider a reflective SLM used as a phase modulating device, using nematic LC. A fully programmable array of phase levels capable of producing arbitrary beam steering, implemented using a grid of liquid crystal pixels. A blazed grating is a convenient example for the study of the diffraction properties of this type of device. The important features of a blazed grating are a linear phase variation in the ramp, and an abrupt 2π phase transition. In addition, it is important that the outcoming polarisation is the same across the area of the whole device for any incoming polarisation, if the device is to function properly in a communication system. Because the input polarisation is undefined no polariser can be used. A quarter waveplate is included between the LC layer and the electrodes to provide polarisation insensitivity [1–3].

To achieve high resolution, pixel dimensions are comparable to the cell thickness and thus the voltage applied to each pixel in order to achieve different phase levels will have a significant effect on its neighbours. This is particularly a problem at abrupt 2π phase transitions. Careful choice of the surface conditions is required to avoid formation of disclinations, where a low surface pre-tilt induces a reversal in director tilt throughout the structure resulting in an ineffective device. Improved device performance is possible through applied voltage adjustments. In this paper we will examine the affect of this discretisation of the potential on the performance of the device.

The orientation of the grating with respect to the pixel grid also affects the switching. An oblique grating will have a rather ragged edge that will affect the diffraction pattern generated by the grating. Additionally, the fringing fields at the edges of the pixels will cause twist and the twisted regions at the border of the pixels will affect the polarisation of the outcoming light.

Experimental assessment of this type of system is difficult, due to the expense of fabrication leading to a need to model these devices. A modelling program [8,9] developed to simulate the dynamic evolution of the LC director in response to an applied electric field has been used to perform two and three dimensional modelling of the director and optical phase modulation to simulate various aspects of reflective blazed phase grating LCOS devices.

2. GRATING PARALLEL TO PIXEL EDGE

First we model a grating with a phase front parallel to the pixel grid. In this case it is possible to perform the analysis in two dimensions. The non-linearity in the switching of the liquid crystal means that the electrode voltages must be specifically calculated to produce the required phase response. As a starting case, ten pixel voltages have been chosen using one dimensional modelling, to give a linear phase output. However, this does not give an optimum solution, as the influence between adjacent pixels is not taken into account. This effect is most severe in the region of the 2π phase transition, and so two-dimensional modelling is required. By systematically modifying the individual pixel voltages, particularly near this region, raising the voltage on one side and lowering on the other, a shorter fly-back can be achieved while keeping a linear phase variation in the ramp [1–3]. Using this method the voltage values for each of the 10 electrodes in the grating period have been found. The voltages have been chosen so that the slope of the phase is kept close to $2\pi/L$, where L is the length of the grating. For satisfactory operation it is not essential for the phase to have a full 2π deviation, and so the voltages have been optimised to meet this first condition and attempting to maximise the phase deviation whilst ensuring the fly back region is contained within 15% of the grating area.

A blazed grating with a period of 10 pixels of pitch 102 μm and a separation of 0.52 μm has been simulated using a 2D method based on a vector representation of the LC director [9]. The 2π transition is located at the centre of the calculation window. The cell thickness is 102 μm, and a quarter wave plate of thickness 32 μm is placed between the LC and the electrodes. E7 has been chosen for the liquid crystal material for the purposes of this simulation. Table 1 gives the elastic and optical properties

TABLE 1 Liquid Crystal Parameters

k11	k22	k33
11.1	10.0	17.1
Viscosity	delta epsilon	epsilon perpendicular
0.007	13.8	5.2
No	ne	Wavelength
1.5	1.689	1.552 μm

for this material. A planar aligned structure with no splay and a 2 degree director pre-tilt on both surfaces has been chosen.

Initial results show the formation of a disclination at the 2□ phase transition, which can be avoided by using a higher value of pre-tilt. From simulations it has been found that a 5 degree pre-tilt is sufficient to prevent the formation of a disclination in this structure. Although this will enable a faster switch-on time of the device, it has the disadvantage of a reduction in the modulation depth. An alternative is to apply an equal voltage to all electrodes before applying the stepped levels, sufficient to ensure the directors switch to an angle above the slope of the electric field lines in the fly-back region. This prevents the disclination formation without requiring a high pre-tilt. A disadvantage is an increase in the switch-on time of the device because of the time required for the director to reach their initial tilt bias.

Figure 1 shows the steady state director profile reached after 20 ms. The directors are represented as cylinders, superimposed on equi-potential contours. The voltages applied to the pixels are shown as part of **Erreur! Source du reuvoi introuvable.**. The 2π phase transition occurs at a horizontal position of 452 μm.

The phase of the reflected wavefront shown in Figure 2 has been calculated including the quarter wave plate between the LC and the electrodes, using the Jones method. The stepped voltages in Figure 2 can be seen to be non-linear across the grating, in particular in the region of the fly-back. On the other hand, the phase of the reflected wavefront is smooth, showing as required a linear ramp for a large part of the grating period. The smoothing effect of the LC allows the device to achieve a linear phase front despite the pixellation. A disadvantage of this smoothing effect can be seen in the fly-back region, where an abrupt change is desired.

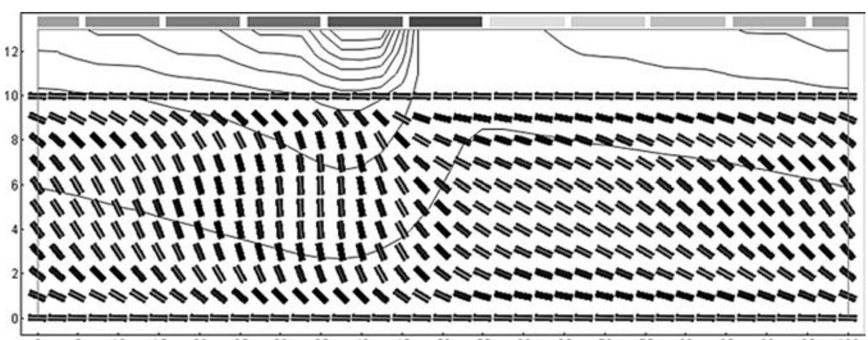

FIGURE 1 Steady state director and potential profile of a 2D blazed grating. Dimensions are in μm.

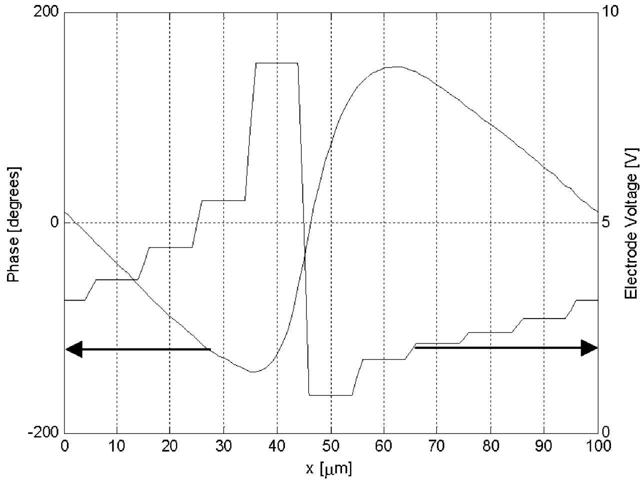

FIGURE 2 Applied electrode voltages and phase of the reflected wavefront.

3. GRATING AT AN OBLIQUE ANGLE TO THE PIXEL GRID

While it is of interest to examine the performance of a programmable 2D blazed grating this does not take full advantage of the capability of the SLM. It is possible to program blazed gratings at other angles to the pixel grid; however it is important to examine this performance, since the pixellation will influence the phase profile that results. For example the presence of twist, which may occur at the edges of pixels at an angle to the phase front of the grating, may affect the polarisation insensitivity of the device. The degree of twist will depend on the surface alignment direction. Two cases have been considered, the first with the director parallel to the pixel edge, and the second with the director at 45 degrees to it.

We analyse next a grating with a phase front forming a 45 degree angle to the pixel grid. The ten voltage values used for one period of the grating

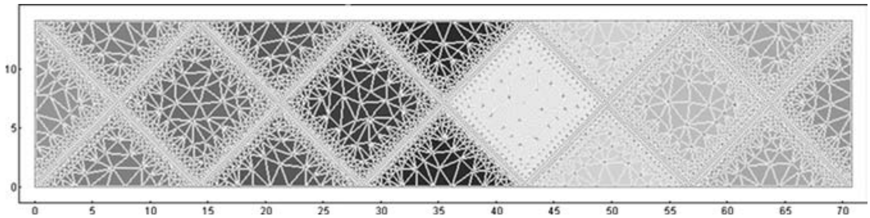

FIGURE 3 Pixel voltage distribution.

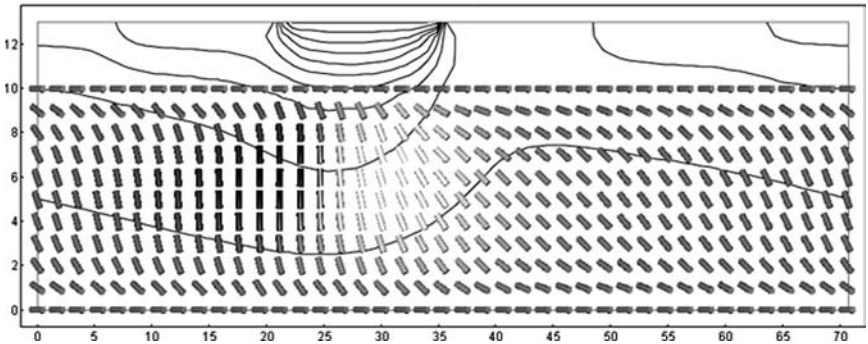

FIGURE 4 Steady state director and potential with pre-twist parallel to the electrode edge pixel grid.

are shown by the shading in Figure 3. Now 3D modelling is necessary [9]. The same potential distribution and LC parameters as in the 2D case are used.

The surface director tilt is configured as in the case of the 2D grating, but now we have a choice of director pre-twist.

Figure 4 shows the director and potential distribution along the centre of the structure shown in Figure 3. The corresponding phase response is shown in Figure 5. A quarter waveplate at 45 degrees to the liquid crystal director ensures polarisation insensitivity as it rotates the plane of polarisation on reflection. However if large amounts of twist are present, the polarisation insensitivity is reduced. This can be illustrated by the degree of uniformity of the polarisation conversion across the SLM. Linearly polarised light would normally be rotated by 90 degrees on passing though

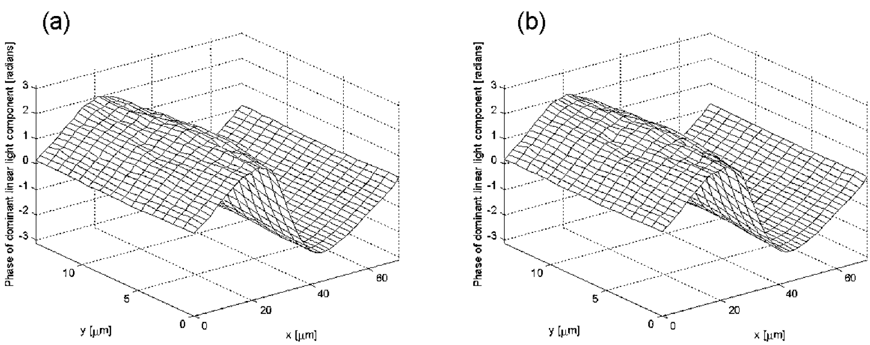

FIGURE 5 Phase of dominant light component with pre-twist at (a) 0, and (b) $\pi/4$ to the electrode edge.

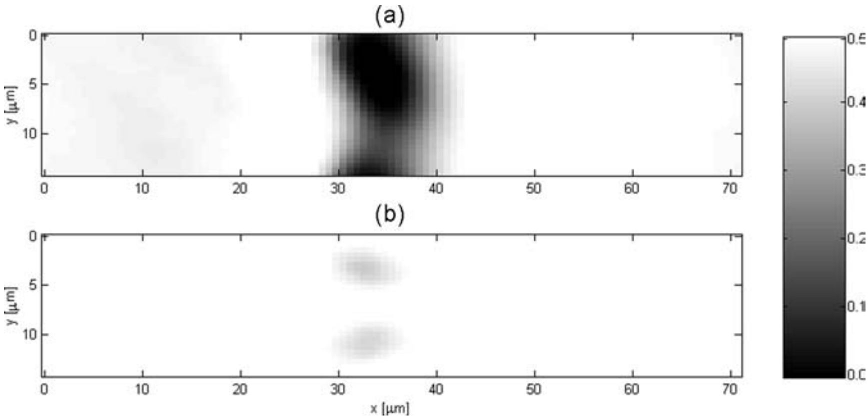

FIGURE 6 Reflectance between crossed polarisers with director pre-twist at (a) 0, and (b) $\pi/4$ to the electrode edge.

the LC and the quarter wave layer (aligned at 45 degrees to the LC director). If twist is present the polarisation may become elliptical.

By calculating the optical reflectance of the cell using crossed polarisers it is possible to observe these regions of polarisation conversion in the cell introduced by the angle of the pixel edge and the grating. Figure 6 shows the reflectance of the cell through cross polarisers for the two cases of surface alignment directions. The results in the figure are calculated using the same window as in Figure 3.

This illustrates the way in which the twist can affect the polarisation conversion depending on the pre-twist of the liquid crystal director at the surfaces.

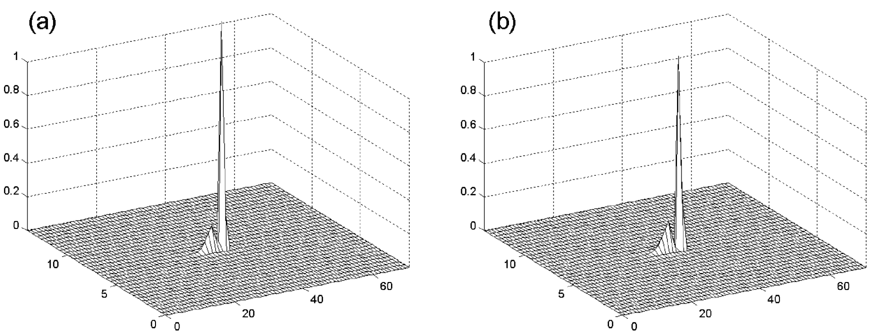

FIGURE 7 Far field pattern with director pre-twist at (a) 0, and (b) $\pi/4$ to the electrode edge. All figures should be 15.5 cm wide, with the exception of figure 2 which is 9 cm wide. The height should be scaled to maintain the aspect ratio.

As a final illustration of the optical performance of the device, the far field pattern has been calculated using the reduced-order grating method (RGM) [10]. Here, the LC cell is regarded as the fundamental cell of a periodic structure in the transverse plane composed of several sub-layers, each characterised by a constant dielectric tensor. This method takes into account both wide angle diffraction and light scattering at the glass-LC interfaces.

The diffraction pattern shows a higher peak when the surface director is aligned along the pixel grid, as the applied potentials have been optimised for this pre-tilt.

4. CONCLUSIONS

A smooth phase modulation can be achieved from a non-linear LC for a blazed grating, using a discrete set of voltages applied to the pixels of an SLM. Selection of the voltages allows control of the behaviour of the phase in the fly-back region. Since SLMs are used as beam steering elements the gratings must be written at different angles to the pixel edges. Accurate 3D director modelling has been used to characterise the performance of such blazed gratings using different director alignment. The diffraction pattern of two examples has been calculated.

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