

Electronically switchable diffractive optical elements

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Liquid crystal filled polymer structure (LiCFiPS) devices consist of a polymer structure, which performs the desired spatial phase modulation of the incident light, filled with liquid crystal to permit modulation of this optical function. Potentially fabrication of this type of device may be carried out at very low cost using established polymer hot rolling or embossing techniques. Devices incorporating complex polymer structures as the diffractive element will inevitably have liquid crystal aligned at varying orientations to the surface. Switchable gratings with the liquid crystal aligned in the plane of the grating but either parallel or perpendicular to the grating rulings have been investigated as the two extremes of alignment. Good quality optical switching has been achieved for parallel aligned devices, however devices with the liquid crystal aligned perpendicular to the grating lines tend to show defects and inhomogeneities. While such devices might not offer the ultimate versatility of matrix addressed SLM devices they do offer electronic control of diffractive optical devices at very low cost.

Keywords: liquid crystal device, switchable gratings, diffractive element, spatial light modulator.

1. Introduction

Liquid crystal filled polymer structure (LiCFiPS) devices potentially offer low cost technology for fabrication of fixed function switchable devices. The devices are essentially a polymer structure between two substrates carrying transparent electrode coatings, the spaces in between being filled with liquid crystal. As the effective refractive index of the liquid crystal changes with applied field the refractive index, and therefore path length difference, between the polymer and liquid crystal regions gives rise to a controlled spatial phase modulation.

The polymer structure may be fabricated using hot embossing or similar techniques which lend themselves to low cost high volume production [1–3]. This polymer structure fixes the spatial phase modulation to be applied to the transmitted optical wavefront, the change in effective refractive index of the liquid crystal filling is then used to modulate or switch this optical function. Though essentially fixed function LiCFiPS devices might be produced in volume using, for example, a continuous embossing roller process and therefore achieve very low unit cost indeed. In volume production the devices may be vacuum or capillary filled.

There are other switchable optical component technologies [4–6], holographically formed polymer dispersed liquid crystal (HPDLC) type devices for example. LiCFiPS has the advantages of extremely low cost, ease of manufacture once the tooling has been made and drive voltages comparable to most LC display devices, a few volts. The

PDLC type devices in comparison have driving voltage requirements of the order of tens or even hundreds of volts.

One of the main problems to be overcome in the liquid crystal device construction being considered here is that of achieving uniform liquid crystal alignment in the presence of the polymer structure's surfaces. Binary optical devices have been demonstrated to date though the situation would be more complex with multi-level devices. This paper presents some measured results that illustrate the potential of these devices but also the need for improved control of alignment on the polymer surfaces in some cases. One of the main problems identified is that in some geometries there is a conflict between the desired liquid crystal alignment and the shape of the polymer structure.

2. LiCFiPS prototype device construction

2.1. Polymer diffractive element

The optical function of the device is determined by the polymer structure. For the prototype devices a polymer diffractive element with the appropriate phase structure was fabricated by photolithography onto a substrate with a transparent electrode. In test devices to date only binary phase structures have been used though in principle multi-level structures might be modulated in a similar way. The diffractive elements in the test devices described were binary phase gratings, though more complex shapes such as Fresnel or Gabor [5] lenses or holographic elements would be possible. It is one of the aims of this work to better understand the alignment effects on such complex polymer structure shapes.

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2.2. Assembly and liquid crystal filling

Another substrate also with a transparent electrode was assembled on top of the polymer structure to produce a closed space that was then filled with liquid crystal. This upper substrate was coated with an aligning layer of Nylon 6,6 which had been rubbed to give a preferred orientation to the liquid crystal. In the prototype devices capillary filling was used as this is particularly convenient with the gratings. For other structures vacuum filling or filling prior to device closure might be necessary.

As the polarisation of the incident light relative to the liquid crystal director changes the effective refractive index of the liquid crystal regions will change changing the phase modulation of the diffractive element. Since the liquid crystal may be reoriented with an applied electric field this phase modulation is then easily electrically controlled. As the cell thicknesses are similar to those in a display device the driving voltages are only a few volts, depending on the liquid crystal used.

2.3. Grating device operation

Grating devices were fabricated in order to investigate the liquid crystal alignment in elementary polymer shapes that were both easy to fabricate and computationally tractable to model. The gratings were fabricated using the commercial photopolymer SU8-2 that has a refractive index at the probe wavelength used (633 nm) of 1.635 though this does vary slightly depending on the polymer curing conditions. The structures that were fabricated were square profile gratings to give a binary phase optical element [7], see Fig. 1.

The gratings allow two distinct cases of liquid crystal alignment to be investigated, first with the liquid crystal aligned along the grating rulings (referred to as parallel aligned) and secondly with the liquid crystal aligned across the grating rulings (referred to as perpendicular aligned). The liquid crystal was aligned by a rubbed Nylon 6,6 coating on only one of the substrates (the other substrate carrying the polymer element), depending on the rubbing direc-

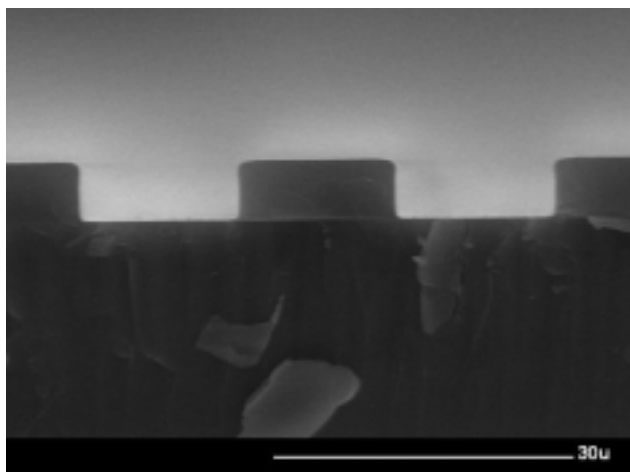


Fig. 1. SU8-2 polymer grating on an ITO coated glass substrate.

tion this gave planar alignment either parallel or perpendicular to the polymer structure direction. The devices were filled with the commercial liquid crystal display material MLC-6200-100 which has refractive indices of $n_{\perp} = 1.507$ and $n_{\parallel} = 1.655$. Since the refractive index of the polymer is between those of the liquid crystal it is possible, by adjusting the incident polarisation to achieve a good refractive index and therefore path length match between the polymer and liquid crystal regions. As the refractive index of the SU8 was dependant on its processing temperature it was necessary to adjust the polarisation in some cases to achieve an index match.

3. Parallel aligned device characterisation

3.1. Far field diffraction characterisation

For devices with the liquid crystal alignment in the plane of the substrates and along the direction of the channels in the grating there is little conflict between the alignment on the substrate surface and the tendency of the liquid crystal to align along the faces of the polymer making up the grating. This configuration is referred to here as parallel alignment. As a field is applied and the liquid crystal molecules reorient they are able to rotate on the faces of the grating without major disruption of the liquid crystal alignment uniformity. This is reflected in generally good switching characteristics even for surfaces with features of the order of 10 μm , Fig. 2(a) and 2(b) show the far field diffracting and non-diffracting states respectively for a parallel aligned 30 μm period grating.

With more coarse gratings changes in the $\text{sinc}(x)$ function envelope of the diffraction orders with applied voltage suggests that the profile of the grating channel is changing

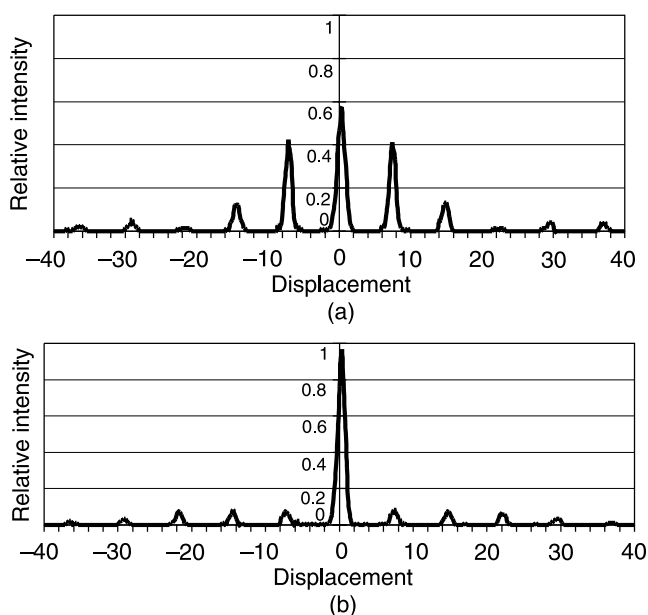


Fig. 2. The diffracting (a) and non-diffracting (b) states of a 30 μm LiCFiPS grating.

as the liquid crystal switches. This has been successfully modelled as a binary phase grating with the mark/space ratio changing with applied field.

3.2 Grating profile modulation model

The assumed grating profile was that of a binary phase grating. It was assumed that the liquid crystal was switching first at the centre of the liquid crystal filled channel with the switched region broadening to fill the entire groove. This gives a binary phase rectangular grating with a varying mark to space ratio [8]. The Fraunhofer diffraction patterns for a grating with a line spacing of 200 μm with the assumed rectangular profiles were computed and compared with the corresponding measured diffraction from the actual grating. Figures 3(a) and 3(b) show the measured diffraction patterns from a 200- μm grating with computed diffraction patterns assuming the width of the liquid crystal region is 40 μm and 55 μm respectively.

3.3. Evaluation

From Figs. 3(a) and 3(b) it is clear that the assumed edge influenced switching of the liquid crystal is correct. It is believed that this type of switching occurs because of the ef-

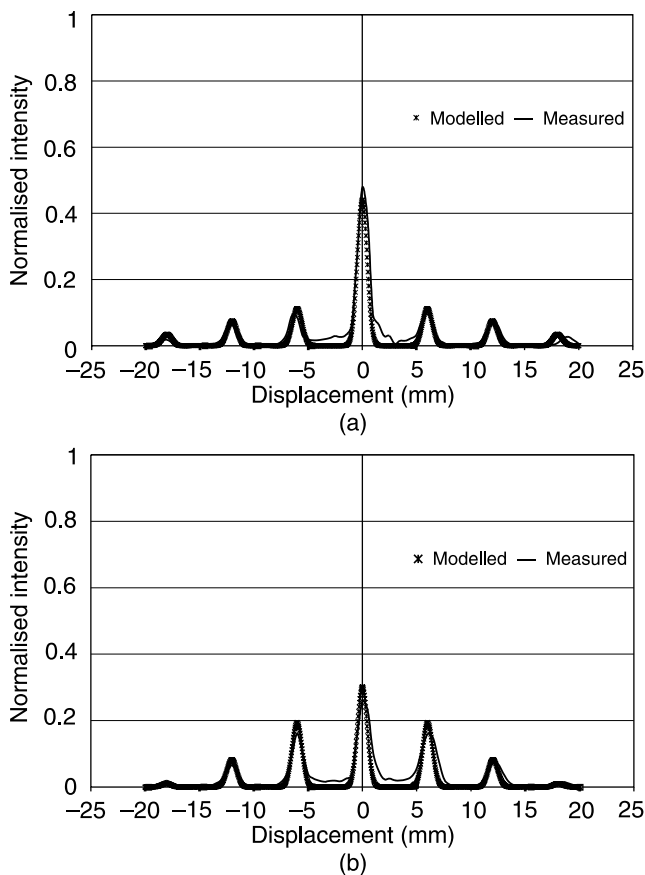


Fig. 3. Measured and computed diffraction from a 200 μm parallel aligned grating with switched liquid crystal regions of (a) 40 μm and (b) 55 μm width respectively.

fect that the polymer faces have on the free rotation of the liquid crystal molecules and on the field locally within the device. The binary phase approximation was very effective as the liquid crystal was a display material that had been optimised to obtain a steep electro-optic characteristic for multiplexing, once switching commenced the liquid crystal would either remain unperturbed or be fully reoriented, very little of the liquid crystal remaining in an intermediate switched state. It has been possible to reliably produce gratings with the liquid crystal aligned parallel with the channels in the polymer, this enables spatial phase modulation of the function defined by the polymer structure and for it to be selected or deselected allowing for optical re-configuration [9]. To produce more complex devices such as switchable holograms or Fresnel lenses there will be some component of the liquid crystal director that is perpendicular to the grating face. Attempts to produce such devices have tended to show defect structures and consequently poor optical switching.

4. Perpendicular aligned device characterisation

4.1. Far field diffraction characterisation

For devices with the liquid crystal alignment in the plane of the substrates but with alignment across the direction of the channels in the grating there is likely to be conflict between the alignment on the substrate surface and the tendency of the liquid crystal to align along the faces of the polymer structure. This configuration is referred to here as perpendicular alignment.

The far field diffraction patterns for perpendicular aligned devices measured under the similar conditions as for the parallel aligned devices show that the liquid crystal is not changing uniformly and a non-diffracting state is not readily achieved. The application of such devices is therefore limited in that it is not possible to achieve on-off switching of the spatial optical phase function.

4.2. Switching behaviour

Figure 4 shows a relatively coarse perpendicular aligned grating device viewed between crossed polarisers, with an electric field of 5 $\text{V}/\mu\text{m}$ applied to the device. In the middle of the grating channel is a zig-zag defect, believed to originate from the conflicting alignment requirement of the liquid crystal to align both across the grating and to align in the plane of the faces of the polymer structure. It is this defect, which originates as a weak defect and is then constrained by the applied field, that ultimately limits the uniformity of the liquid crystal region switching [10]. At very high applied fields the defect may be removed but this also occurs in a very non-uniform way, depending on slight variations in the device surfaces during fabrication.

This defect structure gives rise to non-uniformities and asymmetries that are reflected in the far field diffraction

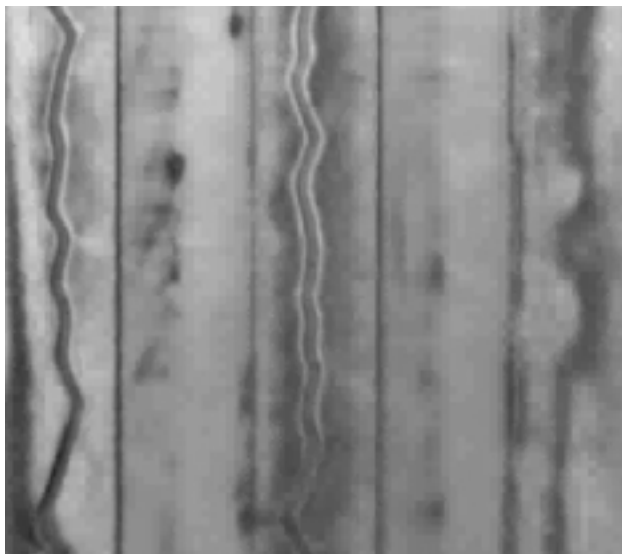


Fig. 4. Image of a 100 μm period perpendicular aligned grating with a field of 5 $\text{V}/\mu\text{m}$ applied.

pattern. Figure 5 shows a typical far field diffraction pattern from a 10 μm period grating with perpendicular alignment. The asymmetry of the switched region gives rise to a bias of the intensity towards one set of diffraction orders rather like a blazed grating. The asymmetry in the grating channel would appear to be consistent across the area of the probe beam as it gives a clearly defined envelope to the diffraction orders. These effects are particularly pronounced in small grating geometries.

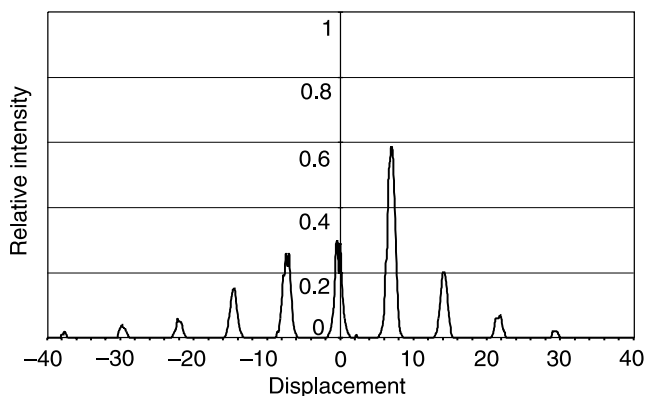


Fig. 5. Asymmetric diffraction from a 10 μm period perpendicular aligned grating.

5. Discussion and conclusions

Though liquid crystal filled polymer gratings with periods of tens of μm have been shown to work well when the liquid crystal is aligned along the grating channel for more complex devices the alignment of the liquid crystal relative to the polymer structure will be more complex. In order to make switchable holographic SLMs using LiCFiPS devices of good quality it is essential to both understand and eradicate or control the occurrence of the defects in the liquid

crystal region of the devices when the alignment is not simply related to that of the polymer structure. Computational modelling work to further understand in detail these interactions is the subject of ongoing investigation.

For applications where the alignment geometry is not a restriction or the optical limitations imposed by the occurrence of defects is not of major concern the LiCFiPS devices offers several advantages. Optically the devices provide a switchable spatial phase modulation and have therefore a high diffraction efficiency though in most cases there will be a polarisation dependence in the optical function. The polymer structure may be produced at very low cost using embossing or similar production techniques and no photolithographic patterning of electrodes is required regardless of the complexity of the optical function to be implemented. As the polymer structure provides an extended spacer the devices are also extremely rugged. Using currently available materials only low driving voltages of a few volts are required for these devices.

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