Projection of holograms from photorefractive OASLMs

Oksana Trushkevych*, Neil Collings, William A. Crossland, Timothy D. Wilkinson, Andreas Georgiou and William I. Milne

Photonics and Sensors Group, Electrical Engineering Division, Engineering Dept., University of Cambridge, 9 J.J. Thomson Ave. Cambridge, CB3 0FA, UK

Liquid crystals doped with fullerenes and carbon nanotubes (CNTs) act as good optical nonlinear materials. We have used these materials to build optically addressed spatial light modulators (OASLMs). The devices comprise of single layer of doped liquid crystal acting as an active layer. Undoped LC devices with surfaces coated with fullerenes are also studied. Such OASLMs allow recording of phase holograms, and we record by imaging pre-calculated pre-recorded holograms. Writing is performed at normal incidence and reading at 45^{o} oblique incidence. Both, transmission and reflection modes of operation are used. Experimental results as well as comparison with commercially available OASLMs are presented.

Keywords: optically addressed spatial light modulator (OASLM), holography, fullerene, carbon nanotube, liquid crystal, optical nonlinear materials, photorefractivity.

Introduction

Spatial light modulators (SLMs) are devices that can record two-dimensional images and erase the previously recorded image. They are increasingly used in many applications including video and display applications[1] and real-time holography[2]. Electrically addressed SLMs are

* or213@cam.ac.uk; phone +44 1223 748347; fax +44 1223 748348; http://www-g.eng.cam.ac.uk/photonics

expensive, and due to limitations on the driving circuitry the number of addressable pixels is limited. To simplify the system, one can address SLMs directly by light.

Optically addressed spatial light modulators (OASLMs) are already commercially available (Hamamatsu[†]). These devices are based on adjacent amorphous silicon and Liquid Crystal (LC) layers. They are relatively simple, but still hard to manufacture and can be used only in reflection at visible wavelengths. Dye-doped LC systems are highly promising materials for novel OASLMs based on photorefractive orientational effects.[3-9] Such devices are intrinsically photorefractive without the need of special layers or circuitry, therefore there are no strict technological limitations on the device area. They can be used in transmission as well as reflection, and measurements show that the resolution of 1-layer dye-doped-LC device can be better than that of the 2-layer amorphous silicon OASLM.[10]

Target characteristics for photorefractive OASLMs are 2π phase modulation and fast switching (e.g. at least 20 ms for video applications). The devices are also expected to have low power consumption, low cost, high resolution (~ 10μm) and good lifetime.

Nematic liquid crystals doped with fullerenes[6,11,12] and carbon nanotubes[13,14] are recognised for their extraordinary large optical nonlinearities with nonlinear refractive index coefficient n_2 up to $20\ cm^2/W$ [11,12]. It is believed that the nonlinearities are due to the reorientation of the nematic director which occurs due to light-induced space-charge field formation aided by the dopant[6].

In this work we report performance of transmissive and reflective photorefractive OASLMs based on a single layer of fullerene or carbon nanotube doped nematic liquid crystals. Undoped LC devices with surfaces coated with fullerenes are also studied. The paper is concentrating on efficiency and demonstrates a proof of principle holographic projection from photorefractive OASLMs.

Experimental procedure

Devices and materials

Nematic liquid crystal materials BLO48 and BLO37 from Merck were doped with C_{60} or octadecylamine functionalised single walled carbon nanotubes from Aldrich. Sonication using Bioruptor from Diagenode was used to promote the solubilisation of C_{60} (30 minutes) and to detangle and disperse nanotubes (5 hours) in case of CNT doping. Materials were sandwiched between two glass slides with transparent ITO electrodes. Cell thickness was 20 μm, and the alignment was either planar (rubbed polyimide) or homeotropic (ZLI 1134 from Aldrich).

There has been a lot of evidence that dopants are adsorbed on alignment layers[11,15,16]. To study the effect of the surface on the device performance, some devices were prepared by depositing weak water solution of C_{60} onto homeotropic alignment as a part of alignment processing on both glass slides, and then filled with pure liquid crystal. We would refer to devices with such layers as "double layer" devices. This device geometry is similar to the one studied by M. Kaczmarek et al[17] where the authors studied C_{60} doped polymers as photorefractive surfaces in LC cell. However, our cells differ by the thickness of the photorefractive layer. Here we imitate dopant adsorption on the alignment surface (which is virtually a monolayer of surfactant) rather than creating a relatively thick photorefractive polymer film.

Our double layer devices are optically transparent, and microscopic study shows some small light scattering particles (too small to be imaged at x200 magnification). The particles are likely to be aggregates of undissolved C_{60} (its solubility in water is only $1.3*10^{-11}$ by weight[18]).

Experimental arrangement

The OASLM contains a non-linear material (in this case a mixture of LC and C_{60} or LC and CNT) therefore its refractive index is related to the strength of the incident beam. A writing beam λ=476nm causes the change in the refractive index which is detected by a reading beam λ=633nm

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† www.hamamatsu.com

by its diffraction pattern. The writing beam is transmitted through a glass slide with hologram that modulates spatially its intensity. This creates an intensity pattern on the OASLM that in turn forms the phase-only hologram on it. Once the reading beam passes through the phase-only hologram (formed on the OASLM) it creates a diffraction pattern that is observed on the screen.

Expanded writing beam (λ = 476 nm, diameter ~1 cm) passes through a calculated binary hologram printed on a slide or glass plate. The hologram is imaged onto a single layer doped LC OASLM at normal incidence. The holograms have smallest feature size 5 μm or 10 μm and are imaged onto OASLMs without magnification.

The intensity of the writing beam at the OASLM is 10 – 60 mW/cm^2. To read the recorded hologram an expanded He-Ne laser beam (λ = 633 nm, 1 mW, diameter ~1 cm) is used in both transmission and reflection mode. Small DC voltage is applied (2 – 4 V) prior to applying a writing beam. Generally, the external voltage should be "on" during the writing and the reading processes. In this study reading is performed simultaneously with writing.

The maximum refractive index modulation is observed by the reading beam incident at the device at 45^o with polarisation in the tilt plane (Figure 1). Note that in planar devices due to the voltage application above Freedericksz transition threshold, liquid crystal director is tilted and approaches homeotropic configuration. As a result, in planar devices the dependence of efficiency on the angle of incidence of the reading beam is smaller than in homeotropic devices. In fact, at certain voltages (~3V) it is vanishingly small.

The devices are non-selective in regard to the writing beam polarisation and very robust to misalignment.

Holograms

The amplitude holograms that imaged the phase-only holograms on the OASLM were designed using the Gerchberg-Saxton algorithm.[19] They were binary amplitude holograms with 512 x 512 pixels with the pixel size 10μm or 1024 x 1024 pixels with the pixel size 5μm making the size of the unit hologram 10 x 10 mm. The amplitude holograms were etched on Al coated glass substrates.

Since an amplitude hologram is used, the reconstruction has a symmetric image and a strong zero order. This is shown in the simulated reconstruction of (Figure 2b). The reconstruction was computed using the Fast Fourier Transform function of the commercial software MatLab. The reconstructed image from a hologram etched on a glass slide is shown on Figure 2c.

When amplitude holograms are projected on liquid crystal cells, a phase-only hologram is formed. Ideal phase-only holograms do not have a zero order and do not produce asymmetric images. Unlike amplitude holograms a phase-only hologram does not absorb or block any light and their efficiency may approach 100%. Hence phase modulating devices are of great interest for improving efficiency.

Efficiency calculation

The main parameter we are interested in is the maximum phase excursion Δ that can be achieved in a device. Phase modulation can be estimated from the diffraction efficiency of the first order for a known grating (e.g. sinusoidal or square grating) is projected onto a sample in Raman-Nath regime[20]. On the other hand, it is possible to monitor optical intensity of the main beam (0^{th} order) and derive phase modulation from its values. Monitoring 0^{th} order is a convenient way to quantify efficiency when projecting holograms instead of gratings.

Neither of these methods gives exactly the phase excursion of the phase-only hologram on the OASLM because they suffer from errors due to scattering and other losses. However, when using both methods, it is possible to minimise the errors. The measurement of phase modulation based on 1^{st} order diffraction from a recorded grating is an underestimation, because of scattering losses, and various causes associated with projection including imperfect contrast and deviations from sinusoidal or square intensity profile resulting in energy being redirected into higher diffraction orders. The second method based on monitoring 0^{th} order gives overestimated values of phase modulation for the same reasons. The real value of phase modulation is between these values.

Optical devices - results

Proof of principle projection and efficiency

We have demonstrated recording and projection of phase holograms from photorefractive OASLMs based on doped liquid crystal layer (Figure 3).

A comparison with commercially available OASLM from Hamamatsu has been performed in the same experimental setup. Figure 4 shows photographs of reconstructed holograms from an original slide with calculated and recorded amplitude hologram, from a reflective Hamamatsu device and from a transmissive single layer photorefractive OASLM.

A simple way of increasing phase excursion in a device is to use devices in reflective mode. This makes both the reading and writing light go through the device twice. Reading at 45^{o} incidence is a very convenient way of operating a reflective device. However the resolution may become an issue. We have built devices with one side Al coated silicon, and ITO coated glass on another, filled with C_{60} doped liquid crystals. Optical experiment has shown a predictable ~2 times increase in the phase excursion. Here we demonstrate the resolution of as high as 5μm (Figure 5a).

The phase modulation values obtained from the measurements of 1^{st} and 0^{th} orders when projecting diffraction grating and 0^{th} order when projecting holograms are summarized in Figure 6. The efficiency of reflective devices (4 and 5) is approximately the double of the efficiency of the transmissive devices of the same thickness and same materials (2 and 3). The highly efficient transmissive device (1) is an aged (since 2002) C_{60} doped BLO48 single layer device, and its performance is exceptional, however we were not able to reproduce a performance of this device in other devices yet. CNT doped device (6) has similar efficiency to C_{60} doped devices (2 and 3); however its dynamics is very different. The double layer device (7) after 2 weeks of ageing has efficiency similar to C_{60} doped devices (2 and 3). Planar aged C_{60} doped device (8) suffers from scattering and therefore has lower efficiency than aged homeotropic device (1). However, this efficiency is still comparable with that of more recent devices (2 and 3).

The best achievable values of phase modulation are $3\pi/4$ in C_{60} doped devices; the target value would be 2π. Homeotropic geometry is beneficial as it suffers less from the hydrodynamic instability leading to scattering. We have achieved good reproducibility of results and devices. Further work on electric switching schemes and materials is in progress.

Time evolution, ageing and stability

Time evolution of C_{60} doped single layer devices leads to some improvement in efficiency. There are no qualitative changes in performance. The time required for device ageing before they started to show high efficiency could be as long as 6 months or more. Recently we were able to greatly reduce the time needed for efficiency improvement as well as get good reproducibility in device production by using advanced dispersion techniques. After initial improvement in efficiency, there are no sizeable changes with ageing, and even devices 5 years old exhibit very good performance. Such stability with ageing is a big advantage from the applications point of view.

Double layer OASLMs based on C_{60} had an interesting time evolution with qualitative change in performance. Initially it was enough to “charge” the device by applying a pulse of DC (selective polarity), and then several writing and reading sessions could be performed without any external field applied. In fact, the application of external voltage during the writing and reading processes lead to scattering. This pre-charge remained for tens of seconds. If wires were grounded or connected together, diffraction ceased abruptly, even with writing light on. This was qualitatively different from the way single layer devices operated. In C_{60} doped devices external voltage (selective polarity) had to be applied at least before and often during writing, and always during the reading process.

After 2 weeks ageing, the performance of the devices changed in the following manner: the efficiency significantly improved; the voltage dependent behaviour became similar to C_{60} doped devices (need to apply external voltage during reading process, fast pre-charge dissipation).

It is likely that with time both - C_{60} doped and C_{60} on surface devices reach a common equilibrium state, which might involve distribution of the dopant next to surfaces or at alignment layer.

Summary

To the best of our knowledge this is the first reported dynamic holographic projection from a transmissive single layer photorefractive liquid crystal OASLM. We have demonstrated optical recording at normal incidence, which is polarisation and misalignment insensitive. The readout is most efficient at 45^o incidence and is polarisation sensitive. It is possible to minimise angular sensitivity of the readout in devices with planar alignment with voltage regime selection.

The ionic content in the devices was minimised which resulted in good lifetime of devices. The onset of hydrodynamic instability was suppressed because of low ionic content and therefore low conductivity, as well as by choosing homeotropic geometry.

The surface phenomena and the positive influence of ageing on the efficiency of the devices is not entirely understood yet, however we were able to reduce the time needed for improvement of performance and obtained good reproducibility of devices by employing powerful sonication to disperse dopants. We demonstrated surface mediated photorefractive response of LC devices with C_{60} - covered alignment surfaces.

Reflective device geometry was employed to enhance phase modulation, and we have demonstrated projection with 5μm resolution in single layer photorefractive reflective OASLMs.

Acknowledgements

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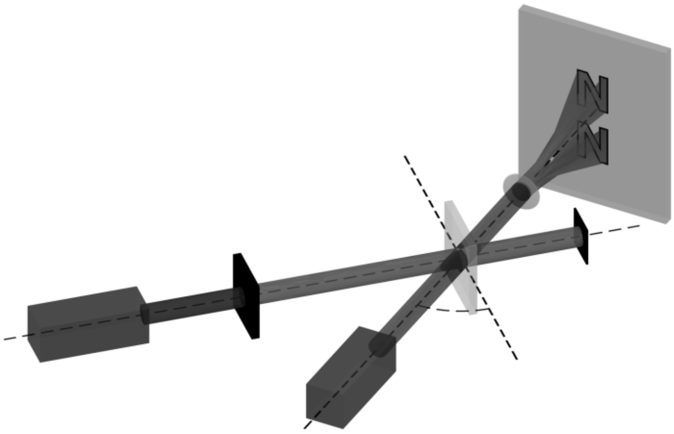


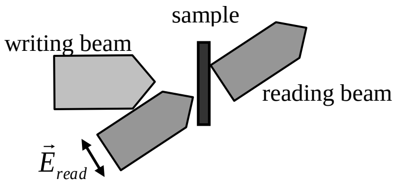
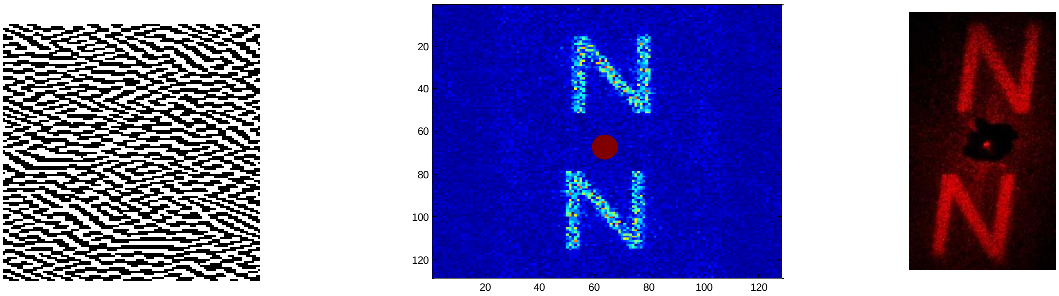


Figure 1. Experimental geometry.



a) b) c)

Figure 2. Holograms used for projection, a) calculated binary hologram; b) its mathematical reconstruction; c) its reconstruction from a physical hologram.

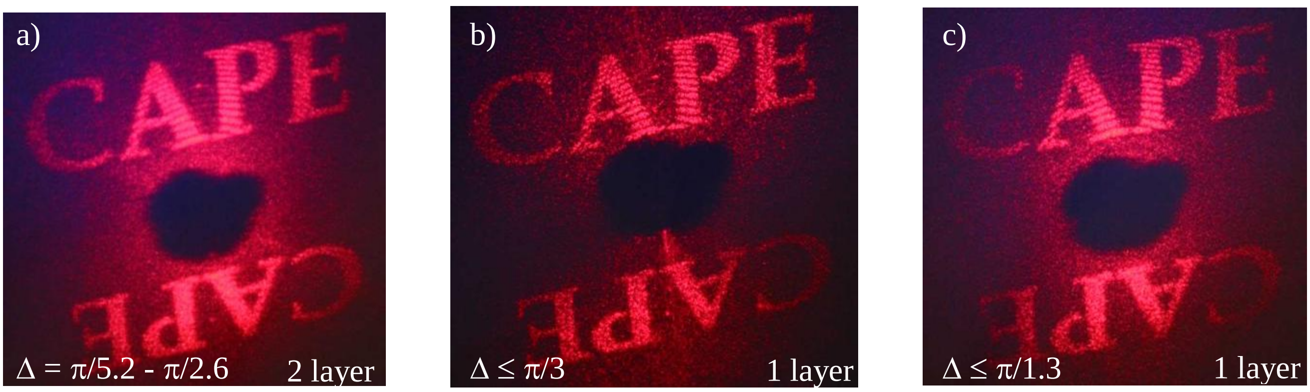


Figure 3 Projection from transmissive OASLMs. The 0th order is blocked for viewing purposes. a) double layer, BLO37, C_{60}-enriched alignment; b) single layer BLO37+C_{60}; c) single layer BLO48+C_{60}

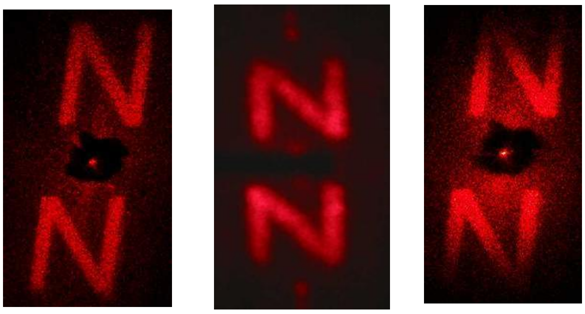


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Figure 4 Comparison with commercially available OASLM. Smallest feature on a hologram is 10μm. a) Projection from calculated and recorded binary hologram; b) Projection from Hamamatsu OASLM X7550, π - 2π modulation; c) Projection from doped LC OASLM, ¾π modulation.

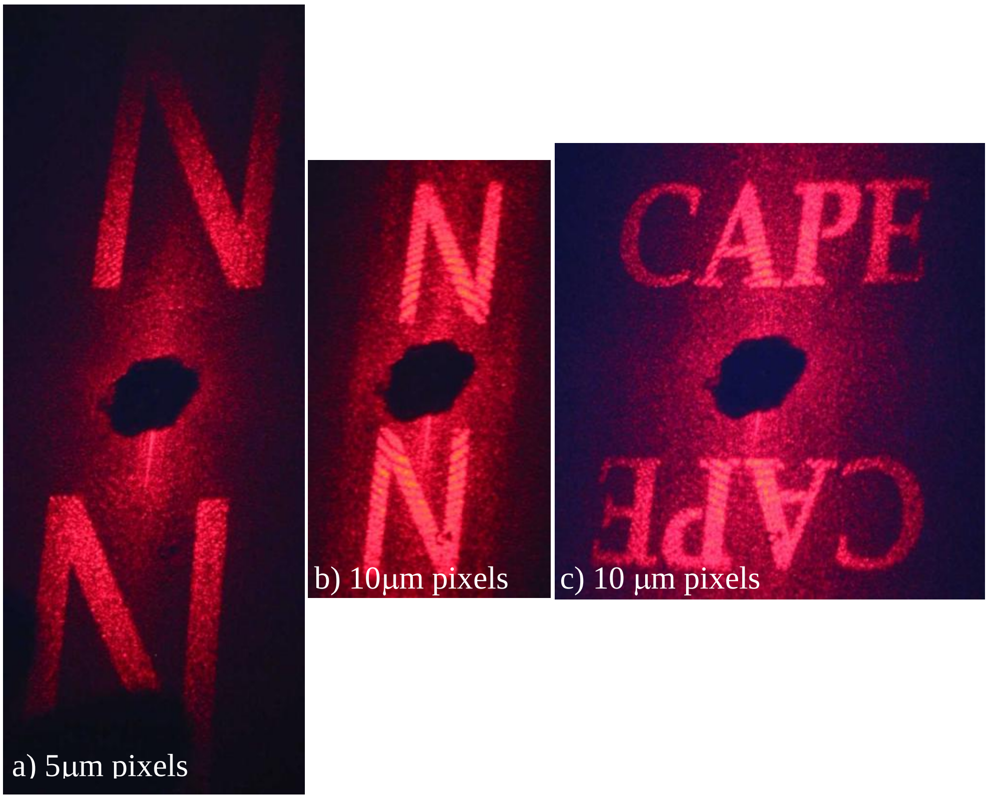

Figure 5 Projection from reflective single layer OASLM (BLO48+C_{60}); writing beam optical power 50mW/cm^2; external voltage 3.6 V_{DC}; the 0th order is blocked for viewing.

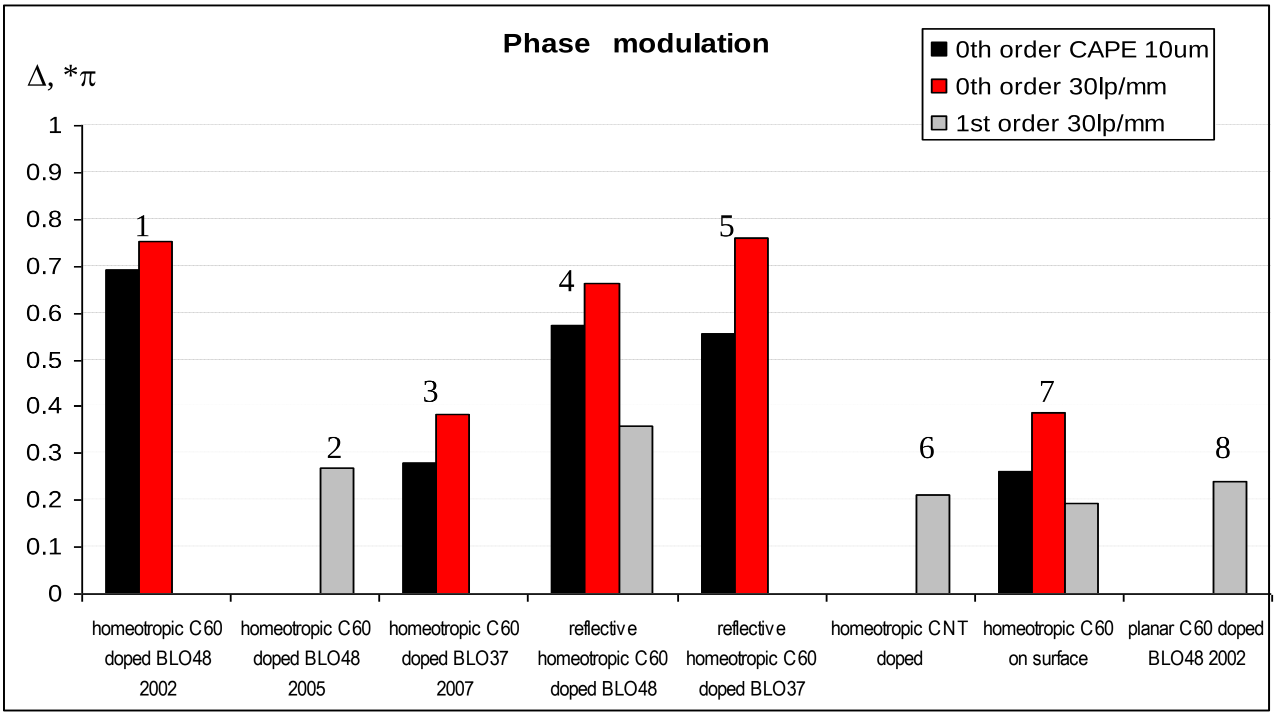

Figure 6 Phase modulation Δ in studied devices, measured by different methods: 30 lp/mm grating and a hologram (letters CAPE). Optical power of the writing beam is 50mW/cm^2.

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List of figures:

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