A novel electro-optic modulator system for the production of dynamic images from Giga-pixel computer generated holograms.

Maurice Stanley*, Pat B. Conway, Stuart Coomber, J. Cliff Jones,
Dave C. Scattergood, Chris W. Slinger, Bob W. Bannister, Carl V. Brown[a],
William A. Crossland[b], Adrian R. L. Travis[b].

DERA Malvern, Malvern, Worcs. WR14 3PS, UK.
[a] Dept of Engineering, Oxford University, Oxford, UK.
[b] Dept of Engineering, Cambridge University, Cambridge, UK.

ABSTRACT

Holographic techniques offer a route to the generation of 3-D images having all the depth cues used by the human vision system. Reconfigurable computer generated holograms allow interactive display of computer held data and synthetic objects. The available number of pixels within the computer generated hologram (CGH) constrains the image size and field of view of such holograms [1] and up to 10^{12} pixels are required to generate full parallax images having widths of ~500 mm and a field of view of ±30°. This has significant implications on both the computation and electro-optic replay of CGH images. To find practical applications, such CGH display systems require electro-optic modulators which deliver a spatial band width product (SBWP) significantly higher than currently available electro-optic modulator or display solutions.

A new electro-optic modulator system has been developed by the authors to replay dynamic holographic images. This Active Tiling™ system offers a route to replay giga-pixel CGH images with video refresh rates. High speed, medium complexity electrically addressed spatial light modulators are combined with a high resolution optically addressed spatial light modulator to provide ultra-high complexity, video frame rate holographic data suitable for coherent readout.

Keywords: Electro-holography, Computer Generated Holograms, Volumetric Display, Spatial Light Modulator, EASLM, OASLM, 3-D Display.

1. INTRODUCTION

It is now commonplace for people to manipulate and work with information in three dimensions within computer environments e.g. CAD, medical imaging, entertainment. However, the normal method of viewing this information is to compute and display a single perspective of the dataset. A major challenge remains to produce solutions for displaying three dimensional computer images in a comfortable and natural way. Any display solution must take into consideration the nature of the information being displayed, the requirements of task, the viewer's environment and the human visual requirements i.e. depth cues. Additional problems arise if multiple people wish to share the same 3-D information, particularly if normal human interactions are not to be impeded.

The human vision system infers depth from a range of cues available within the scene. Whilst it is acceptable for one or more depth cues to be absent from a scene, it is important that cues which are present should be consistent. A number of these depth cues can be reproduced on high fidelity 2-D images. These psychological cues e.g. occlusion, known size, shading and shadows, and object motion, are learnt by the viewer through their life and do not require viewing with two eyes. Current 2-D rendering techniques and displays implement these cues very successfully.

* Correspondence: Email: mstanley1@dera.gov.uk; WWW: http://www.dera.gov.uk; Telephone: (44) 01684 895422; Fax: (44) 01684 896530.

In *Practical Holography XIV and Holographic Materials VI*, Stephen A. Benton, Sylvia H. Stevenson, T. John Trout, Editors, Proceedings of SPIE Vol. 3956 (2000) • 0277-786X/00/$15.00

The physiological depth cues exploit physical actions of the observer when viewing the scene. Such actions include the focusing of the eye (accommodation), eye convergence, binocular disparity and movement of the viewer (motion parallax). When the viewer consciously or unconsciously acts, a corresponding change in the perception of the scene is expected to occur. 3-D display techniques are being developed to re-create one or more of these physiological depth cues. None of the display solutions fully reproduce all of the depth cues, and many result in conflicts which result in loss of depth realism, errors in depth estimation, and in the worst case can result in discomfort to viewers. Holography is the only 3-D display solution which has the ability to recreate all psychological and physiological depth cues in an unambiguous manner.

2. HOLOGRAPHY MODULATOR REQUIREMENTS

Holography, as initially described by Gabor [2], captured both phase and amplitude of optical wavefronts from objects by interfering a wave from a scene or object with a reference wavefront. The resulting interference pattern recorded in a photosensitive plate can be used to reconstruct a duplicate of the original object wavefront by diffracting light from the reference beam. Viewers perceived this reconstructed wavefront as though it had originated from the original three dimensional scene. It has been found that high fidelity holographic images with a wide field of view required holographic recording materials e.g. silver halide with very high resolution. The information content of such holograms is extremely high – more than 10^{12} bits per cubic cm. Clearly this information content is significantly beyond any current or anticipated display or computer system. However, it can be argued that such images contain significant redundancy and contain detail that the human visual system is incapable of resolving. A challenge for developers of digital hologram systems is therefore to isolate the essential information content before developing efficient computing and display hardware.

Computer algorithms have been developed [1] which calculate the holographic interference pattern from a three dimensional computer held data sets e.g. CAD data. These algorithms either numerically replicate the optical hologram recording process or more efficiently, numerically replicate the hologram replay process. At present, CGHs can be written into photosensitive layers by laser plotter, and replayed using coherent illumination. A typical image replayed from a laser plotted CGH is illustrated in figure 1. Whilst computing requirements are currently very high and form a bottleneck to practical exploitation, the algorithms are developing rapidly and are being optimised for available computing hardware. However, a second critical bottleneck is the ability to display the image in real time due to the limited performance of electro-optic modulator systems.



Figure 1. Illustration of CGH image computed from CAD data.

The number of pixels required by a holographic display solution is not obvious to deduce and depends strongly on the application.. Two routes to estimate the magnitude of the problem can be made. The first is based on an analysis of the number of points in a $(0.5m)^3$ volume which could be resolved by an observer 10 cm away. This suggests that the CGH requires $\sim 10^9$ pixels. The second route is based on diffraction analysis of a thin hologram producing an image of a given size and field of view, as shown in figure 2.

The field of view $\Delta\theta$ of the image I is related to the CGH size W (in one dimension) by

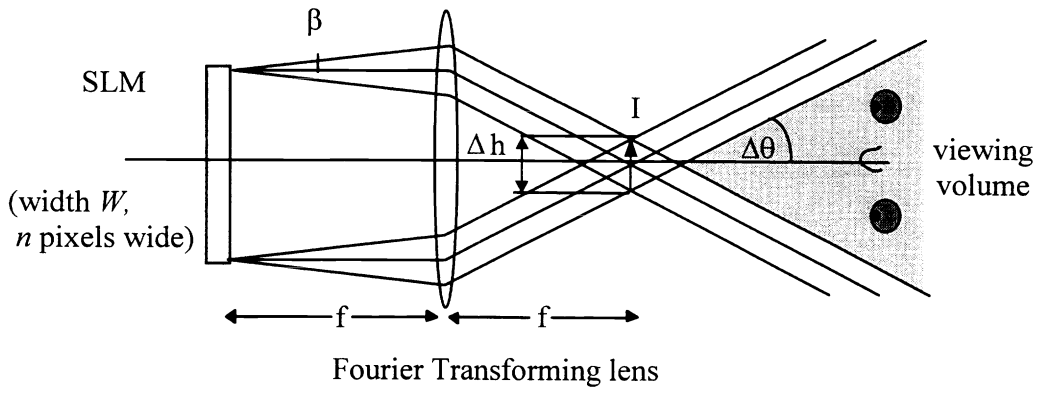


Figure 2. The Fourier CGH replay geometry

$$\Delta\theta = \tan^{-1}\left(\frac{W}{2f}\right), \tag{1}$$

and the size of the image volume Δh was related to the pixel pitch of the CGH, p

$$\Delta h = \frac{\lambda f}{p}, \tag{2}$$

where the number of pixels along one side of the CGH is given by

$$n.p = W. \tag{3}$$

From the product of equations 1 and 2

$$\Delta h \cdot \Delta\theta \approx \frac{n.\lambda}{2}, \tag{4}$$

it could be deduced that, for small angles, the total number of pixels along one side of the CGH determines the product of image size and field of view in that axis. Equation 4 predicts that the product $\Delta h.\Delta\theta$ is independent of both the pixel size in the spatial light modulator and subsequent magnification optics, although the above calculation only considers a simple Fourier hologram system, and there are more efficient replay configurations. This equation was used to estimate the worst case pixel requirements for a holographic display system producing an image $(0.5\text{m})^3$ with a 60° field of view. Equation 4 predicted that a horizontal parallax only system would require a pixel count of $\sim 10^9$ pixels, and a full parallax system would require a pixel count up to 10^{12} pixels. It is desirable for such images to be replayed at video rates, and so the target spatial bandwidth product would be a minimum of 10^{10} bits per second. This is significantly greater than the performance of the leading modulator systems to date.

Electro-holography display systems have been reported which demonstrate the state of the art in their respective modulator technologies. One of the best known, developed at MIT [3], exploited two 18-channel acousto-optic modulators (AOMs) to scan a laser beam in the horizontal axis, and flapping mirrors for vertical deflection. This technique achieved a pixel count of 38 M pixels with a display refresh time of 40 Hz. This system produced horizontal parallax only (HPO) images 140 x 80 x 150 cm in size with 144 lines of vertical resolution. In principle, acousto-optic modulators offer a high system bandwidth – several hundred Mbits per second can be delivered by a single AOM. However, the information is output in a serial fashion and large mechanical scanning systems are required to convert this into a holographic image.

A second example of an electronic holography display system, developed by the TAO consortium [4], exploited a number of commercial off-the-shelf (COTS) liquid crystal display (LCD) modulators. Up to 5 active matrix liquid crystal projection display panels were seamlessly tiled together within the coherent replay beam. This coherent tiling technique achieved a pixel count of 15.5M pixels on a 28 micron pixel pitch and an update rate of ~30 Hz. This display was configured to produce HPO holographic stereogram images typically 40 x 150 x 50 mm in size. Coherent tiling of LCD components offers a scaleable modulator solution for hologram replay, but in practice COTS LCD products have insufficient uniformity for coherent replay systems. In addition, active matrix LCDs require a transistor at each pixel which limits their pixel density and results in very large optics to achieve the required pixel content.

The performance of alternative electro-optic modulator technologies was reviewed to assess their potential to meet the demanding requirements for electronic holography, as illustrated in figure 3. The diagonal lines represent equal space bandwidth product.

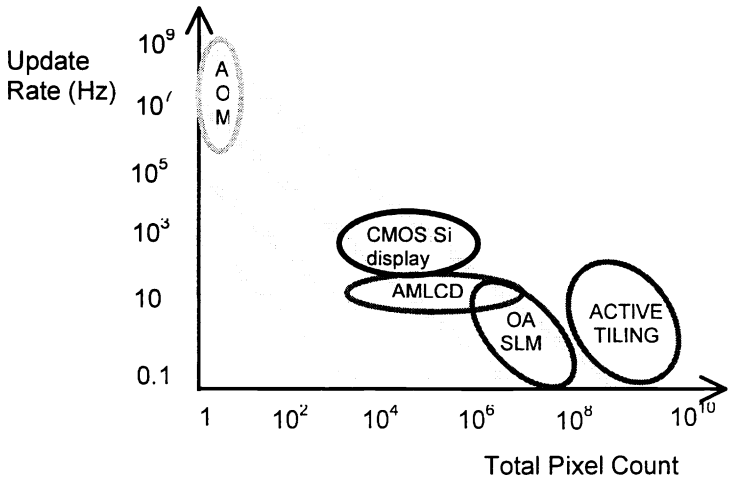


Figure 3. A comparison of electro-optic modulator performance.

Over the last couple of years, data graphics projectors based on reflective CMOS silicon chips have emerged which exploit both liquid crystal on silicon (LCOS) and micro-machined silicon optical modulation techniques. A number of these technologies, e.g. TI's Digital Micro Mirror, or ferroelectric liquid crystal (FLC) on silicon display are high frame rate binary display modulators and offer typically 1 million pixels updated at frame rates in excess of 1 kHz. This corresponds to a spatial bandwidth product (pixel count x refresh rate) in excess of 1Gbit/s, which compares favourably against acousto-optic modulator systems. As an example DERA have developed a ferroelectric liquid crystal (FLC) on silicon chip [5] which has displayed in excess of 10^4 frames of data per second. This high speed performance is exploited in video projectors through the use of temporal dithered greyscale and frame sequential colour generation, and commercial EASLMs are currently available with ~1M pixels at 10 - 20 μm pitch. Whilst higher complexity display chips with 3-4 million pixels are being developed, such devices are not likely to produce the pixel counts required for electronic holography in the near future. In addition, these COTS components do not generally meet the flatness requirements for coherent replay systems.

Passive addressed liquid crystal display technologies such as τ-V_{min} addressed ferroelectric LCDs avoid the requirement for a transistor at each pixel. This enables very small pixels to be produced, and 4 micron pitch had been demonstrated by the authors. However, signal propagation down narrow ITO tracks resulted in degradation of addressing voltage, and the system refresh rate was determined by the line address time of the FLC material. It would be very difficult to achieve video update rates for devices with significantly more than 2000 lines of information. An alternative liquid crystal modulator technology is that of Optically Addressed SLMs (OASLMs), which have been exploited in projection displays as well as optical signal processing systems. Data patterns must be written optically onto the OASLM, and has been achieved using direct interference of object and reference beams, by X-Y scanning of a focused laser beam, or using cathode ray tubes. Holographic images have been successfully replayed on OASLMs [6]. However, the techniques used to write information onto the OASLM to date have been very slow or have not exploited the full potential of these devices.

3. THE DERA ACTIVE TILING™ MODULATOR SYSTEM

Active Tiling is a scaleable electro-optic modulator solution which exploits the high frame rate of medium complexity, electrically addressed spatial light modulators (EASLMs) and the high resolution of optically addressed spatial light modulators (OASLMs) to produce a system which can display images or patterns with significantly higher pixel count than previously possible. In this system, some of the temporal bandwidth of the EASLMs was traded off for spatial bandwidth at the OASLM, enabling higher pixel counts to be written whilst maintaining video update rates overall.

The Active Tiling system is composed of a number of key components:

- EASLMs which act as an 'image engine' to rapidly display the CGH image segments;
- Replication optics which project multiple demagnified images of the EASLM onto the OASLM;
- OASLMs to build up and display the complete CGH pattern;
- Readout optics to form the holographic image, and a control system to synchronise the complete system.

The modulator system works by breaking up large CGH data sets into segments which are displayed sequentially on an EASLM. These data segments are then projected onto the photosensor of a liquid crystal based OASLM through the replication optics to form multiple images of the EASLM at the OASLM photosensor. One of the image segments can then be stored on one region of the OASLM by switching the liquid crystal at that region. A new data segment is then loaded onto the EASLM and transferred to an adjacent region on the OASLM, as illustrated in figure 4, until a complete image has been written. This process can write a high complexity, high resolution CGH pattern on the OASLM which can then be read out by coherent illumination to replay the hologram.

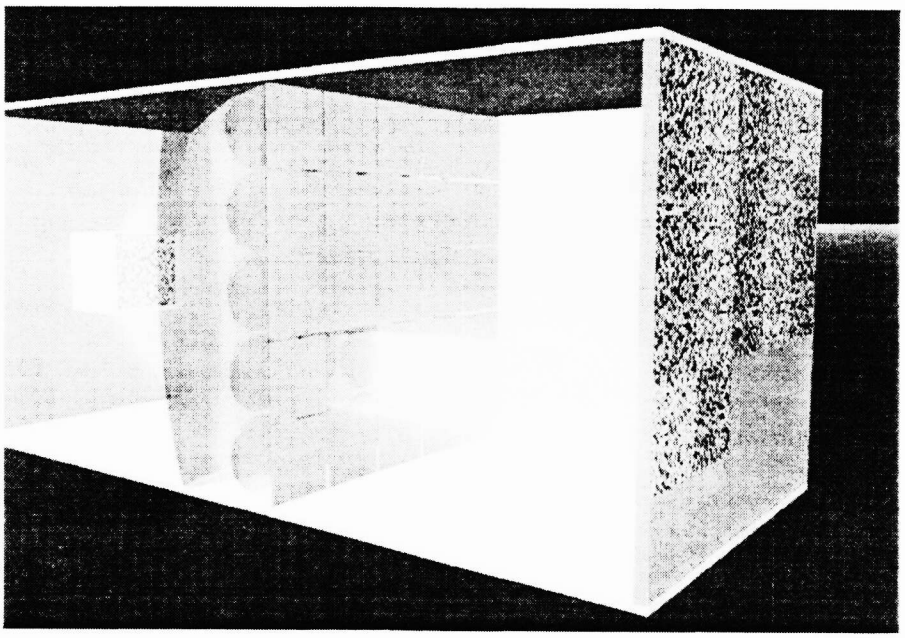


Figure 4. The Active Tiling™ system.

To illustrate how complex images can be produced, a 2k x 2k pixelated EASLM shall be considered. Projecting images from this device through a 5x5 replication optical system would form an image containing 10k x 10k (or 10^8) pixels. However, the replication optics system itself was designed to be modular to enable multiple channels to be assembled in parallel to produce a seamless image of arbitrary size. A system containing 10 x 2 modules would result in a pixel array containing over 2 Giga pixels. In this example, the total image can only be updated at a rate of 1/25 that of the original EASLM(s). A number of COTS EASLM technologies can operate with frame rates in excess of 1 kHz which result in a total CGH image update rate greater than 40 Hz. Because of the highly parallel architecture implemented in this system, it is possible to run each module independently and each EASLM would receive data from it's own host computer interface. Whilst the total Active Tiling system spatial bandwidth product could be in excess of 80 Gbits/s, each of the parallel data feeds would operate at bandwidths equivalent to current high-end graphics monitors, enabling the system to exploit COTS graphics hardware. Through this technique it is possible to write giga-pixel holographic images updated at video rates.

3.1 Electrically Addressed Spatial Light Modulators

CMOS silicon based EASLMs offered a number of attractive features for replaying holograms within Active Tiling as well as a plentiful supply at relatively low cost. A key benefit of these CMOS silicon based displays was that the silicon backplane contained all of the device addressing circuitry and could support very high data rates. In addition, these devices offered pixel sizes between 10 and 20 microns due to the transistors being fabricated from higher quality silicon. However, they were not ideal for direct hologram replay as the pixel density was still too low for a practical holography system, and in addition these COTS components did not generally meet the flatness requirements for coherent replay systems.

The Active Tiling system was initially developed using the DERA Fast Bit Plane SLM [5] which displayed 240 x 240 pixel image segments through a replication optics system to produce an output image of 1200 x 1200 pixels on a FLC on silicon OASLM. The EASLM was operated with an image update rate of ~2kHz which resulted in a system update rate greater than 40 Hz. Recently, a new system has been developed which exploited the Displaytech LightCaster™ SXGA display chip [7], originally developed for video projection applications. This new display chip provided 1280 x 1024 pixels (although only 1024 x 1024 were used) on a pitch of 13.7 μm and was driven via a custom interface to update images at typically 1 kHz.

3.2 Replication Optics System

A number of techniques to produce an array of images have been described in the literature [8] including lens arrays, diffractive optical elements e.g. Dammann gratings, holographic optical elements, beamsplitters and electro-optic scanning techniques. A refractive lens array solution, shown in figure 5, was developed by the authors as this provided a high degree of aberration control and system flexibility. This was based on a double lens design where the first lens group collimated the light diverging from the EASLM, and each lens within the array produced a image of the EASLM. The optics system was designed to demagnify the data pattern from the EASLM to exploit the superior spatial resolution of OASLMs, which significantly reduced the overall system volume.

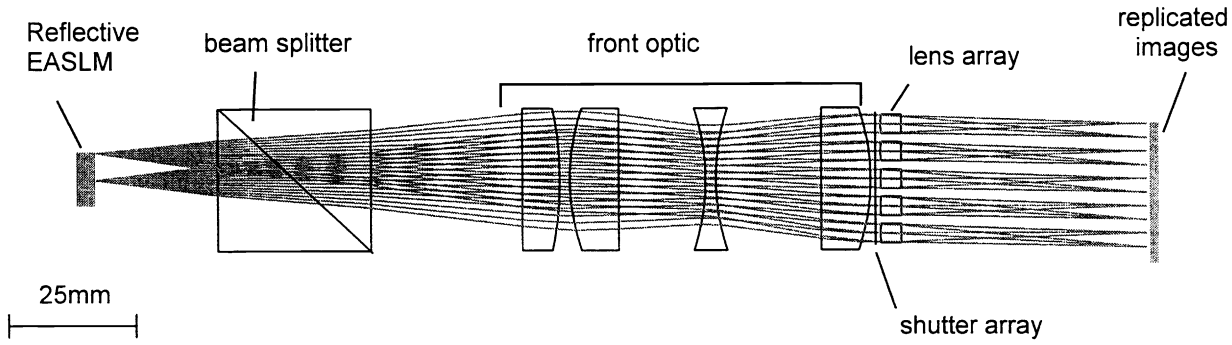


Figure 5. The replication optics system.

A 5x5 optical replication system with 50% image demagnification was designed and built to match the physical dimensions of the Fast Bit Plane EASLM. This achieved 80% power within a 13μm point spread function across the image field. This system produced an image at the OASLM photosensor plane containing 1200 x 1200 pixels at 17μm pitch. A critical constraint on the optics system was that the replication optics should not extend laterally beyond the $(20.4mm)^2$ replicated image at the OASLM. This demonstrated that the complete optics system could be assembled in modules to form a more display system and yet preserved a continuous image on the OASLM.

A second replication optics system is currently being developed to utilise the Displaytech SXGA EASLM to produce a seamless 5120 x 5120 pixel CGH pattern at the OASLM with a pixel pitch of less than 7 μm. This new replication optics system has been based on a 5x5 array of Cooke triplet lenses, and has resulted in a system which achieved 5 μm point spread function at the OASLM plane. The number of replications used in the system was chosen to be the optimal

combination for image uniformity and aberration control within the replication optics, and also provided acceptable CGH image update rates greater than 20 Hz. Again the replication optics did not extend laterally beyond the replicated image array to maintain the system modularity.

To achieve consistent switching across the OASLM, it was necessary to achieve uniform power density of the write light across the OASLM plane. Spatial illumination uniformity across the EASLM ensured uniform power density within each replicated image, and controlled convergence of the EASLM illumination ensured that each lens channel within the replication array received equal optical power. An illumination arrangement was implemented using a rectangular light pipe whose dimensions were optimised for the EASLM and collimating lens.

Decoupling the EASLM from the CGH coherent replay plane via the replication optics offered a number of key benefits when replaying holograms, including:

i. The EASLM does not modulate coherent light, and so the system can exploit lower specification projector based components.
ii. The EASLM was operated with monochromatic light, which enabled higher EASLM and shutter performance to be obtained.
iii. The pixel pitch at the OASLM was modified using demagnification in the replication optics, allowing the OASLM to be written at higher spatial resolutions than available from commercial EASLMs.
iv. The EASLM can be protected from high power readout illumination.

3.3 Optically Addressed Spatial Light Modulators

OASLMs offer a number of intrinsic features which make them highly suited to replay holograms. A description of OASLMs and their operation can be found in the literature [9], and will only be summarised briefly here in order to highlight these benefits. The structure of a typical OASLM is shown in figure 6, and comprises of a thin 2-D photosensitive layer, typically hydrogenated amorphous silicon, and a thin liquid crystal modulation layer. These layers are formed on the inside of a glass cell which has transparent conductive electrode layers. Reflective and/or light absorbing layers can be deposited between the silicon and liquid crystal layers to enhance the device reflectivity and prevent optical cross-talk. Almost any liquid crystal modulation mode can, and has been used within these devices.

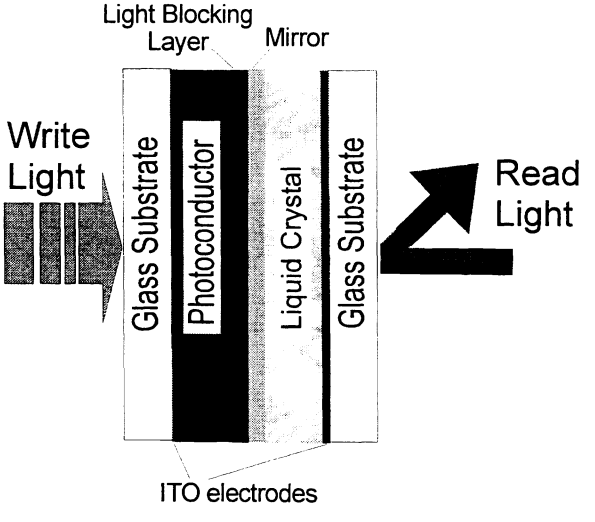


Figure 6. A typical OASLM Structure.

The thickness and conductivity of the layers can be arranged so that when a voltage is applied to the structure in the dark, the photoconductor layer has the highest resistivity and there is insufficient voltage across the liquid crystal layer for it to switch. When light is incident on the photosensor, charge is generated in the conduction band and its resistivity falls to a level below that of the liquid crystal. The liquid crystal layer now experiences the applied voltage and switches in the region

where light was incident. The image which has been written in the liquid crystal layer can then be read out by a separate laser source.

OASLM devices have been exploited in high performance video projectors and optical signal processing systems, but are also highly suited to holography. A major feature is that they are based on continuous 2-D layers and have the ability to display very high resolution information without the requirement for complex CMOS addressing circuitry. Resolutions in excess of 200 line pairs per mm have been demonstrated in several OASLM configurations [6,10]. Another significant benefit of their simple 2-D layer structure is that they are highly suited to low cost, large area fabrication without requiring high resolution lithographic processing. In addition, the unstructured photosensor layer is advantageous for uniform liquid crystal cell fabrication and has the necessary flatness for coherent readout. The OASLM device can also act as a two dimensional light 'buffer amplifier' which enables incoherent to coherent image conversion, wavelength conversion and image amplification.

Within the Active Tiling system, coherent illumination is only used to readout the OASLM, whereas the image writing was implemented with monochromatic incoherent illumination. This minimised speckle noise, and also lowered the tolerances of the EASLM and replication optics system. This is particularly beneficial if multiple EASLM modules are to be combined incoherently to extend the system performance.

3.4 Image storage in OASLMs.

A critical function of the OASLM was to store the information within each data segment whilst the remaining information was loaded. The complete hologram image could be read out only after all of the data segments have been loaded. It is possible to display a sequence of CGH images at video rates to create an animation sequence. However, if the image is not to be changed then the CGH image may be repeatedly readout without erasing and reloading the data.

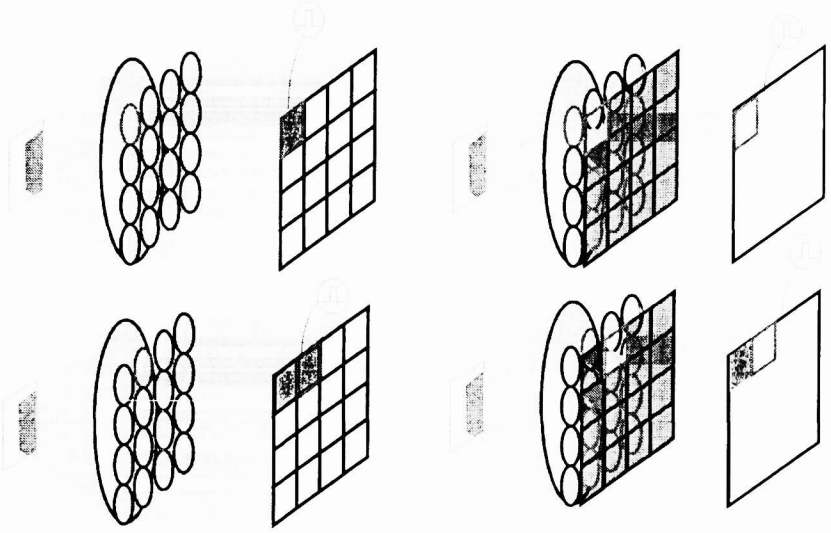
Images may be stored in OASLMs using several techniques. These include the use of bistable liquid crystal modulation modes, or through control of the charge lifetimes within the photoconductor. Surface stabilised ferroelectric liquid crystal technology provided fast modulation rates with either binary phase or amplitude modes, and also used a very thin liquid crystal layer. In reflection mode of operation, this FLC layer was typically 1 μm thick which enabled very high resolution patterns to be accurately display on the OASLM.

Two mechanisms were identified to select image segments for storage on the OASLM, as illustrated in figure 7. One technique exploited the voltage switching threshold of the OASLM. In this mode, one or both OASLM electrodes were lithographically patterned to exactly match to the image segments. When a CGH data segment was displayed on the EASLM, it was replicated on all segments of the OASLM, and voltage selection pulses were applied to the OASLM segments where the image was to be stored. Any region of the OASLM not receiving a voltage pulse did not change the switched state of the liquid crystal.

A second image selection technique which exploited the optical switching threshold of the OASLM could also be implemented in the refractive lens array system. In this mode of operation, the OASLM electrodes were continuous across the active area of the device and only regions which were required to switch received light from the EASLM. A ferroelectric liquid crystal shutter array positioned immediately after the lens array, and an individual image segment was selected for loading onto the OASLM by opening only the corresponding pixel within the array. Light from all other channels was prevented from reaching the OASLM photosensor.

4. SYSTEM SPECIFICATIONS and APPLICATIONS

An Active Tiling system was developed and replayed holographic images from data patterns written on the OASLM. The first system, based on the DRA Fast Bit Plane EASLM had a relatively low number of pixels compared to the target system, and consequently the reconstructed image was small and had a restricted field of view. Due to this limitation, a second system is being developed which exploits state of the art EASLM devices. This new system is achieves the target performance of a single Active Tiling module of 26 Mpixels with a pixel pitch of less than 7μm, with video update rates. This is equivalent to a spatial bandwidth product of 0.5 Gbits per second. This level of performance can be achieved through exploitation of COTS display technologies and their interfaces and is not unique to, nor dependant on any single EASLM technology. Indeed, this system will readily exploit future developments in projection display components, including new



(a) (b)

Figure 7. Image selection techniques within Active Tiling™ using either (a) electrical or (b) optical selection.

technologies, as they emerge to meet future conventional display requirements. In anticipation of these developments, work will continue to focus on extending the performance of an Active Tiling module and also combine multiple modules to increase the overall pixel count of the replayed hologram.

In summary, Active Tiling provides a route to significantly extend the performance of electro-optic modulators which is critical to develop a practical electro-holography display system. A potential workstation display system would need to produce a holographic image which is ~ 0.5m in size and is comfortably viewable from ~1m or arm's reach. To achieve this a display system would require in excess of 10^9 pixels to give an acceptable viewing zone for horizontal parallax images, or up to 10^{11} pixels for a full parallax hologram. These levels of performance are possible using Active Tiling. An example workstation concept is shown in figure 8.

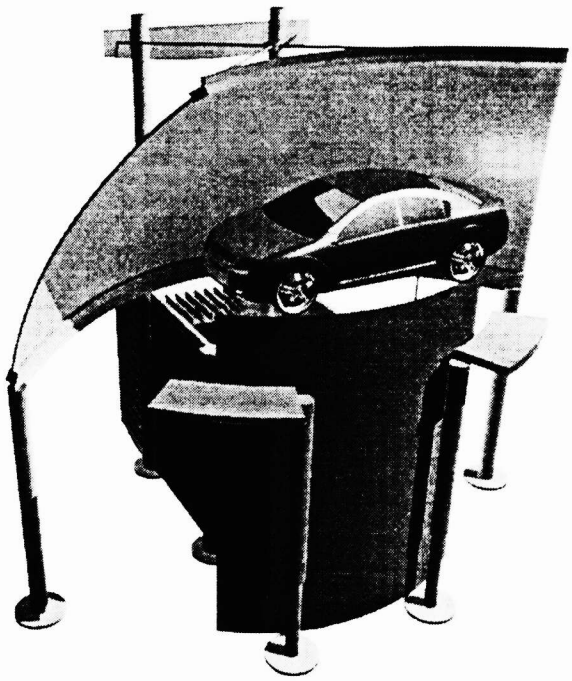


Figure 8. An illustration of a holographic workstation concept containing 100 Active Tiling modules.

ACKNOWLEDGEMENTS

This work was carried out as part of Technology Group 7 of the UK MoD Corporate Research Programme, and also with the support of the Ford Motor Company. Technical support was gratefully received from members of the Volumetric Imaging team at DERA, the DERA Optics facility, and members of the Photonics Group at Cambridge University. A number of the images in this paper and the video were produced by Glasgow School of Art's Digital Design Studio.

REFERENCES

1. For example: M. Lucente, "Interactive computation of holograms using a look-up table", *Journal of Electronic Imaging,* **21**, pp28 – 34, 1993; or N.J. Phillips, C.D. Cameron, A.K. Dodd, D.A. Pain, D.T. Sheerin, C.W. Slinger, Proc. SPIE **3637**, *Practical Holography XIII*, p.33-44, 1999.
2. D. Gabor, "Microscopy by reconstructed wavefronts." *Proc. Roy. Soc.* **A197**, pp454-487, 1949.
3. P St-Hilaire, S.A, Benton, M. Lucente, J. Underkoffer and H Yoshokawa, "Realtime holographic display: improvements using multichannel acousto-optic modulator and holographic optical elements", Proc. SPIE **1461**, 1991.
4. K Maeno, N Fukaya, O Nishikawa, K Sato, T Honda, "Electroholographic display using 15M pixels LCD", Proc. SPIE Vol. 2652 *Practical Holography X,* pp15-23, 1996.
5. W.A. Crossland, T.D. Wilkinson, T.M. Coker, T.C.B.Yu and M. Stanley "The Fast Bit Plane SLM: a new ferroelectric on silicon SLM deigned for high yield and low cost manufacturability", OSA TOPS **14**, *Spatial Light Modulators*, p102, 1997.
6. S. Fukushima, T. Kurokawa, M Ohno, "Real time hologram construction and reconstruction using a high resolution spatial light modulator", *Appl. Phys. Lett.*, **58** (8), pp787-789, 1991.
7. Displaytech Lightcaster™ SXGA display. www.displaytech.com.
8. K.Hamanaka, H. Nemoto, M Oikawa, E. Okuda, T Kishimoto, "Multiple imaging and multiple Fourier transformation using planar microlens arrays.", *Appl. Opt.* **29**, No. 28, pp 4064-4070, 1990.
9. U Effron Ed. *Spatial Light Modulator Technology: materials, devices and applications*, Marcel Dekker Inc., New York, 1995.
10. N.L. Ivanova, A. P. Onokhov, A.N. Chaika, V.V. Resnichenko, D.N. Yeskov, A.L. Gromadin, N.A. Feokyistov, L.A. Beresnev "Liquid crystal spatial light modulators for adaptive optics and image processing" Proc. SPIE. **2759** *Advances in Optical Information processing VIII*, 1996.

© British Crown Copyright 2000. Published with the permission of the Defence Evaluation and Research Agency on behalf of the Controller of HMSO.