

## Recent advancements in photorefractive holographic imaging

**B Lynn<sup>1</sup>, P-A Blanche<sup>1</sup>, A Bablumian<sup>1</sup>, R Rankin<sup>1</sup>, R Voorakaranam<sup>1</sup>, P St. Hilaire<sup>1</sup>, L LaComb, Jr.<sup>1</sup>, M Yamamoto<sup>2</sup> and N Peyghambarian<sup>1</sup>**

<sup>1</sup>College of Optical Science, University of Arizona, Tucson, Arizona 85721, USA

<sup>2</sup>Nitto Denko Technical Corporation, Oceanside, California 92054, USA

E-mail: blynn@optics.arizona.edu

**Abstract.** We have recently demonstrated several improvements in material properties and optical design to increase the resolution, size, brightness, and color range of updatable holograms using photorefractive materials. A compact system has been developed that is capable of producing holograms with brightness in excess of 2,500 cd/m<sup>2</sup> using less than 20mW of CW laser power. The size of the hologram has been increased to 300mm x 150mm with a writing time of less than 8 seconds using a 50 Hz pulse laser. Optical improvements have been implemented to reduce the hogel size to less than 200  $\mu\text{m}$ . We have optimized the color gamut to extend beyond the NTSC CIE color space through a combination of spatial and polarization multiplexing. Further improvements could bring applications in telemedicine, prototyping, advertising, updatable 3D maps and entertainment.

### 1. Introduction

Three dimensional (3D) displays are becoming more prevalent by the day, with entertainment systems providing a semblance of three-dimensionality already flooding the consumer market. The motion picture industry has stepped in as well, integrating stereoscopic filming and post-production depth enhancement in some of the latest feature films. Standard two dimensional (2D) displays integrate many of the depth cues that a viewer uses to judge distance and relative position, such as shading, occlusion and linear perspective, yet the more subtle but equally important cues like parallax, stereopsis and convergence are omitted. By integrating this second set of depth cues into a 3D display the viewer is provided with a more physiologically natural method by which to assimilate the information, ensuring a richer viewing experience. The speed and accuracy at which a user can perform a task has been shown to increase when presented in a 3D format rather than a 2D format [1] indicating significant possible benefits for uses in fields such as medicine [2], terrain perception [3] and complex data analysis [4].

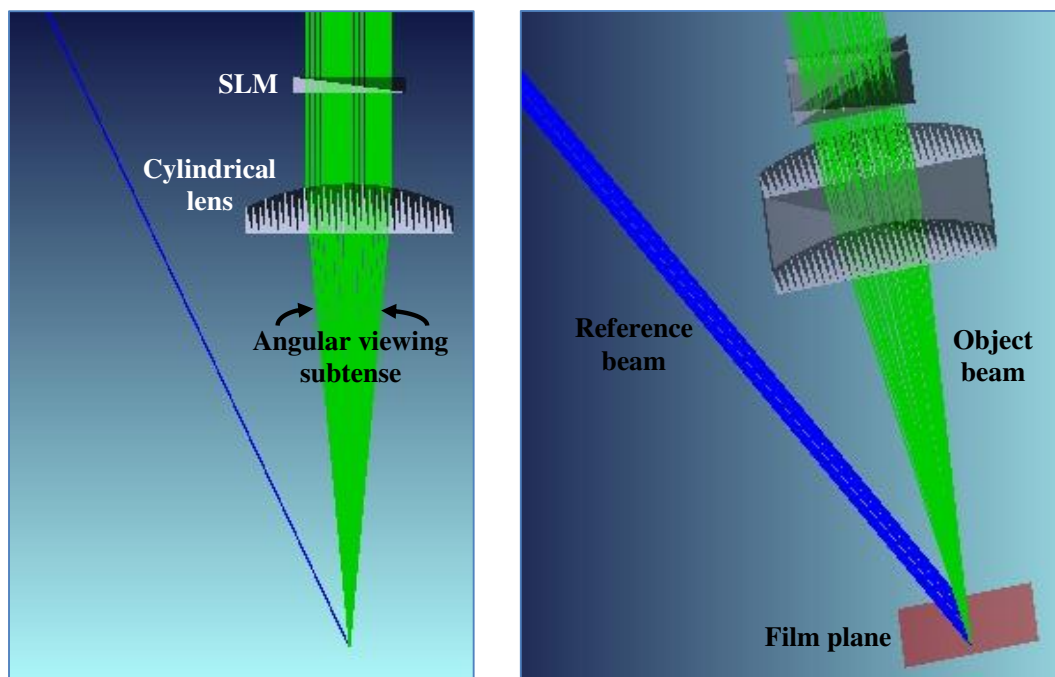
Many approaches to creating 3D displays have been seen over the recent decade, with a majority of the systems falling into one of three categories as defined by Holliman et al [5]. These are two-view systems, horizontal-parallax systems and full parallax systems in which the distinction is made based on the degree of parallax that the system is able to display at any one point in time. Head-mounted displays and those requiring eyewear to achieve the 3D effect fall into the two-view taxonomy while the horizontal and full parallax systems present multiple views of a scene, allowing the viewer to look around an object. As the number of views presented to the viewer increases, the reproduced scene begins to approach a true representation of the original scene, eliminating the vergence-accommodation conflict when the wavefront of the projected image approaches that of the

object [6,7]. A hologram is the ideal truly 3D display, reproducing the amplitude and wavefront of a scene with resolution only limited by that of the recording media [8]. Computer generated holograms have also been exhibited [9], eliminating the need for direct holographic recording of an object in order to reproduce it. The main drawback to holography is that it is based on diffraction from features that are on the scale of the wavelength of the illuminating light, or around 500nm for a visible display. This pattern must be reproduced in some updatable fashion at the desired refresh rate, requiring the display media to have high-speed, sub-micron resolution with a size suitable for viewing, or on the order of  $10^{12}$  pixels for a 20 inch display. For a 3 color, 8-bit display updating at 30Hz, this means transmission of  $10^{16}$  bits per second. In contrast, a 1080i HDTV with the same display parameters only needs a pipeline that can transmit  $10^7$  bits per second.

Due to this high bandwidth requirement, conventional computer generated holographic displays do not appear to be practical at this time, but significant effort has been expended to develop approximations retaining the realism of holographic imaging. One way to reduce the computational complexity of the system is to remove the phase information from the wavefront reproduction, leaving only the intensity and direction to be recreated (light field reproduction), as in holographic stereography [8]. This technique has been used to produce very realistic representations of scenes and is the technology upon which our updatable display is based.

## 2. The Holographic Printer

Holographic stereograms, also known as integral holograms, are created by holographically recording views of a scene or object taken from different angles. In our holographic printer, the necessary views of a 3D model or scene that will be reconstructed are processed into hogels, or holographic pixel elements as described in prior work from our group [10]. The hogels are uploaded to a spatial light modulator (SLM) which is used to structure the object beam of a holographic recording system. This object beam is focused onto the film plane by a lens, creating the angular subtense of the image and is there interfered with the reference beam to create an interference pattern, the basis of the hologram.



**Figure 1.** Representative illustrations of the main holographic printer components and organization. The reference beam is illustrated in blue to distinguish it from the object beam.

Figure 1 shows an illustration of this holographic interference concept for a horizontal parallax only system, as noted by the cylindrical lens and the line focus on the film plane. The full parallax system replaces this cylindrical lens with one that is circularly symmetric, illuminating a square hogel on the film. Illumination with an LED source from the correct angle reproduces the recorded model for viewing. In our case, the media into which we record the interference pattern differs from that used in other types of computer generated holograms.

Silver halide and photopolymers have often been used as the recording film but images in these media are permanent. In order to create a dynamic and updatable display using holographic stereography, the recording media must be able to record and display the image, but also erase and record/display a new image. Photorefractive materials fit this bill, enabling continually refreshing scenes to be holographically recorded and displayed, with photorefractive polymers being the best material for a large viewing area. The photorefractive polymer media is based on a composite of a hole transporting polymer doped with a non-linear optical chromophore, a plasticizer and an optical sensitizer. The polymer is then melt-processed between two transparent electrodes creating the photorefractive film onto which we record the holographic stereogram. The material composition and film preparation method have been described in previous literature [11]. When the interference pattern from the writing system illuminates the film, the intensity distribution is recorded nearly instantaneously into the media, resulting in a refractive index distribution and allowing us to reconstruct the 3D image by diffracting the reading illumination from the index grating.

### **3. State of the art performance**

#### *3.1. Brightness*

Display brightness plays an important role in the comfort of the user, with low luminance levels contributing to eye strain and fatigue. In order to be a viable system, any display must be able to reproduce the illumination levels that are present in current day computer monitors and televisions. Standard computer monitors and televisions are designed to be viewed in a variety of ambient illumination levels, from a darkened room to outside viewing conditions and produce luminance levels in the range of 300-1000 cd/m<sup>2</sup>. Our current system is illuminated with a Luminus color LED reaches a luminance of greater than 2,500 cd/m<sup>2</sup> in the image plane, indicating that it is more than sufficient to meet the range of desirable brightness levels any user could need.

#### *3.2. Reduced Laser Power*

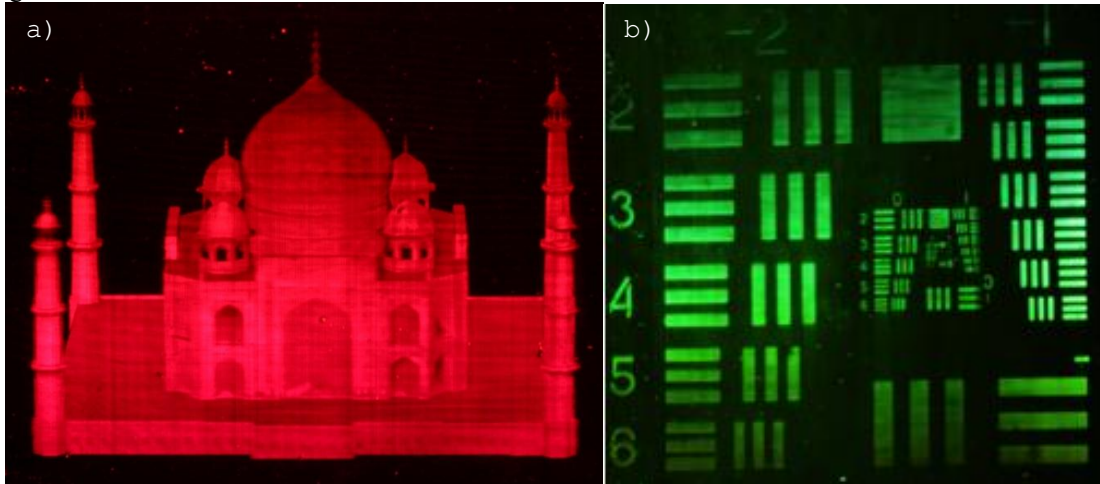
The sensitivity of our current system has increased dramatically, with significantly less laser power required to record images. In previous work [10, 12] we reported a pulse laser output power of 10W in one iteration and in another iteration 100mW/cm<sup>2</sup> CW laser flux measured at the film surface. Now our total laser power for the CW system is less than 20mW, with the flux at the surface significantly less accounting for the various losses throughout the system. One major benefit for reducing the laser power needed to write an image is that it reduces the overall energy requirements of the display system.

#### *3.3. Increased Display Size*

Display size is another of those factors that plays an important role in usability of a system. As a display increases in size, the quantity of information that can be displayed without compromising the viewability also increases. Additionally, larger displays can more easily accommodate multiple viewers at one time. We are successfully moving toward larger displays with our system architecture and our photorefractive film material lends itself nicely to scaling to larger screen sizes. In the previous iteration of our system, we recorded and displayed an image on our 100mm x 100mm sample, taking approximately 2 seconds to record using a 6 ns pulse laser with a repetition rate of 50Hz [12]. In our current work we can write and display an image on a 300mm x 150mm sample in less than 8 seconds using the same pulse laser.

### 3.4. Improved Resolution

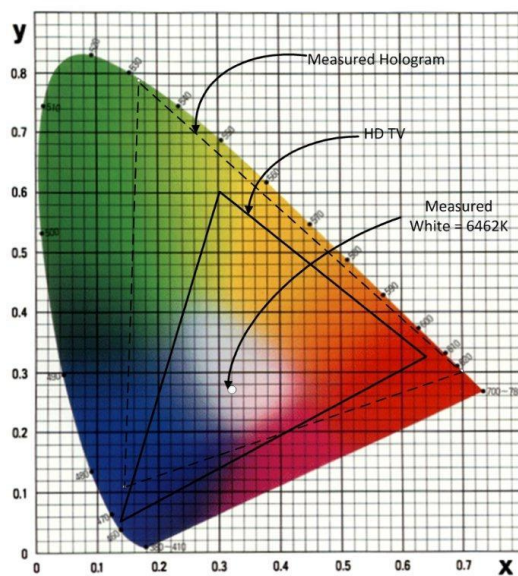
In previous work, we reported images written on the CW display with a resolution of 0.8mm hogel requiring illumination time of one second per hogel [13]. Currently, we are able to achieve hogel sizes of less than 200 $\mu\text{m}$ , taking only 0.4 seconds to write each hogel on the CW display. This improvement in horizontal resolution allows us to more accurately reconstruct higher frequencies in the horizontal direction. The vertical resolution is only constrained by the resolution of the SLM which for this system is on the order of 110 $\mu\text{m}$ . Figure 2 shows pictures of holograms taken with a digital SLR.



**Figure 2.** Pictures of holograms recorded with 200 $\mu\text{m}$  hogels a) the Taj Mahal and b) an Air Force test target used to measure the size of the hogels [14]

### 3.5. Optimized NTSC CIE Color Space

One benefit of the illumination scheme of this display is that we are able to reconstruct the image with any wavelength using LED sources. We are currently using three Luminus LEDs with nominal



**Figure 3.** CIE color space comparison for a standard HDTV vs. output measured from our hologram



**Figure 4.** Photograph of a three color hologram written on our system

wavelengths 632nm, 525nm and 460nm, combining to provide a crisp white at 6462K. This gamut far exceeds that of the standard HDTV as shown in figure 3, allowing a larger range of colors to be reproduced by this display. Figure 4 shows a photograph of a three color hologram written by our display system and illustrates a number of vivid colors.

#### 4. Conclusion

Our holographic stereogram display is fast approaching a near video-rate display with vastly improved brightness, display size, resolution and color gamut all while decreasing the laser power necessary for recording. Though our photorefractive polymers have shown sufficiently fast response times for video rate refreshing [15] current laser technology falls short of our need for kHz pulse repetition rates and tens of mJ per pulse. Additionally, the move toward a faster updating SLM or the like would allow us to increase the system refresh rate for the three color systems. We continue working toward increasing the sensitivity of our polymers as well as reconfiguring the optical designs, advancing our progress toward a 3D updatable video-rate display.

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