Avenues for Expanded Applicability in Photorefractive Based Holographic 3D Displays

C. W. Christenson[1,*], P.-A. Blanche[1], R. Voorakaranam[1], A. Bablumian[2], J. Thomas[1], M. Yamamoto[3], R. A. Norwood[1], N. Peyghambarian[1]

[1]*College of Optical Sciences at the University of Arizona*
[2]*TIPD, LLC, Tucson, Arizona*
[3]*Nitto Denko Technical, Oceanside, California*
[*]*cchristenson@optics.arizona.edu*

Abstract: The first updatable three-dimensional holographic display based on a photorefractive polymer device, exhibiting a fast response, long persistency, and phase stability is discussed. Material and optical setup changes for new and broader applications are outlined.

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1. Introduction

Three-dimensional (3D) perception is fundamental to the human interaction with the physical world. Our brain is accustomed to viewing and processing in 3D, and when information is presented in two-dimensions, there is a fundamental deterioration in understanding. This is especially important in the areas of industrial design, medical imaging, military simulators, and terrain mapping. Holography is a powerful technique that allows complete reconstruction of the wavefront of light scattered from an object, making it appear as if it were actually in front of the viewer.

Hologram recording systems have advanced from static materials with excellent sensitivity, such as silver halide and dichromated gelatin, to dynamic systems utilizing acousto-optic materials [1]and liquid crystals [2]. Unfortunately the former class is not refreshable and the latter do no exhibit persistency, among other limitations. Photorefractive (PR) polymers have the potential to fulfill these requirements. They have been extensively studied over the last decade and have a wide range of applications [3-5]. In a PR polymer, the interference pattern created by two coherent beams causes charge generation in the illuminated areas, followed by transport and then trapping in the dark regions. The resulting spatial charge distribution creates local electrical fields which orient nonlinear and/or birefringent molecules, leading to a macroscopic refractive index change (a phase hologram).

In this paper, the development of the first updatable 3D holographic display based on a photorefractive polymer [6] will be summarized, and the advances necessary to make this material viable for a wider range of applications, including pulsed writing and full-color displays, will be introduced.

2. Experimental Methods

The photorefractive polymer composites developed and studied contain a copolymer as the hole-transporting host matrix. The copolymer approach is taken to reduce the phase separation typical in guest-host polymer systems with low T_g, thus allowing increased loading of functional components such as NLO chromophores. The copolymer consists of a polyacrylate backbone with pendant groupstetraphenyldiaminobiphenyl-type (TPD) and carbaldehyde aniline (CAAN) attached through an alkoxy linker (PATPD-CAAN). A fluorinated dicyanostyrene (FDCST) NLO chromophore was added to provide sufficient refractive index change and charge generation at the wavelength of interest (532nm). The plasticizer N-ethyl carbazole (ECZ) was also used to reduce the glass-transition temperature to approximately room temperature.

Samples were made by melt processing a composite of PATPD-CAAN/FDCST/ECZ (50/30/20 wt%) between two indium-tin-oxide coated glass slides. The thickness was set using 105μm spacer beads. The sample showed neither phase separation in an accelerated aging test at 60^0C for 7 days, nor degradation or damage for several months over hundreds of write/erase cycles.

The 3D display hologram is generated using integral image holography. Dozens of 2D perspectives of a object are processed on a computer to produce many holographic pixels (hogels). The hogels are spatially multiplexed onto the sample, and when reconstructed produce a sensation of depth via parallax. This technique allows a 3D image to be constructed from multiple 2D images without the real object needing to be present. This is an efficient technique, but the phase information of the scattered light is lost. Recording is performed with a frequency-doubled Nd:YVO_4 laser at 532nm, which falls within the absorption band of the chromophore. The beam is split into two paths, an

object beam and a reference beam. The object beam is modulated with the hogel information using a spatial light modulator and focused in the horizontal direction. The nature of human vision is such that the 3D effect can be accurately reproduced using only horizontal parallax, so the hogels are vertical stripes. The reference beam is collimated and made to interfere with the object beam in the sample. The total writing intensity was 100 mW/cm^2. The entire hologram is written by recording hogels side-by-side across the width of the sample. The hogel width is 0.83mm, and for a 4in x 4in sample, there are 120 hogels. The writing time for each hogel is 1s, though the damping time for vibrations from the translation stage must also be considered, so a dwell time of about 1s is added prior to writing. This sets the total writing time to 3-4 minutes. After writing, the sample is translated to a new position and the hologram is read using a 650nm LED lamp. The low coherence length producesnegligible speckle and the low absorption reduces erasure. The hologram can be erased at any time by uniformly illuminating it at 532nm.

For the desired applications, it is beneficial to have a material that can be written quickly but decays very slowly. In order to facilitate this, a technique called voltage kick-off has been developed [6], in which a large voltage (typically 9kV) is used during the writing to increase speed, while a decreased voltage (typically 4kV) is used for reading to increase persistency. The steady-state efficiency from four-wave mixing is about 50% at 9kV, but the dynamics show an intermediate peak in the efficiency at 10% after 1s of writing. If the writing beams are turned off and the voltage reduced to 4k at this time, the efficiency continues to increase in the dark as the space-charge field and chromophore orientation continue to develop. This kick-off technique permits a hogel writing time of 1s in a material with a longer time constant, and increases the persistency of the hologram.

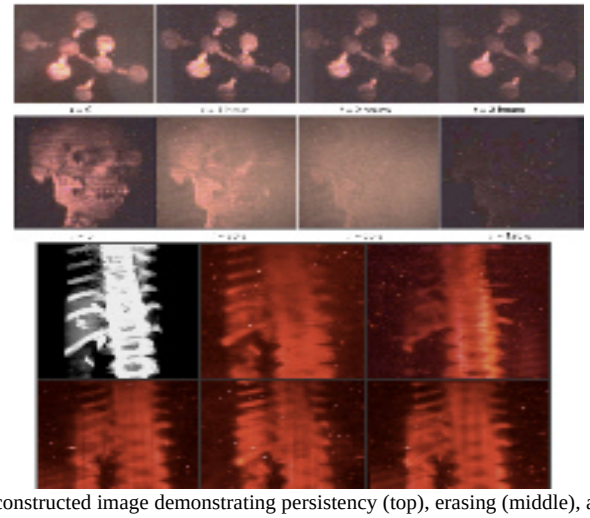

Fig. 1. Some pictures of the reconstructed image demonstrating persistency (top), erasing (middle), and parallax (bottom two rows).

3. Results and Future Applications

Some images from holograms recorded in a 4in x 4in sample are shown in Fig. 1. The top row shows the image of an ethane molecule is still visible after 3 hours of continuous viewing. The second row shows that an image can be completely erased in 30s, and the bottom two rows are images of a spine x-ray taken at different camera angles to demonstrate the parallax of the 3D image. Note that these 2D snapshots are only a modest reproduction of the experience upon viewing the actual hologram.

In order to fully utilize the potential of holography for the commercial and governmental applications discussed above, several improvements in both the material and writing geometry will have to be made. This includes having a full-color hologram that is viewable in white or ambient lighting conditions, decreasing the writing time to video rates, increasing the viewing angle, and increasing the size of the device. Using well established polymer chemistry and processing techniques, the last point can be relatively easily achieved.

A full-color hologram will require first material changes. Currently, the absorption below 500nm is too high in this and most chromophores to observe any transmission with the eye, so a new sensitization component or scheme will need to be developed. While this is perhaps the most difficult step, the optical recording setup will also require changes. Currently, one grating is recorded in a transmission geometry, with a grating spacing on the order of micrometers. The grating has a certain wavelength selectivity based upon this spacing [7]. In transmission for this particular polymer device, the change in the Bragg-matched wavelength with a change in the reading angle is around

tens of nanometers per degree. This means if a non-collimated polychromatic source is used to read one recorded grating, multiple colors will be diffract. This can be overcome at the cost of using multiple monochromatic reading sources. The broad dispersion also means the grating for each color can be recorded at the same wavelength, angularly multiplexed to separate any cross-talk.

In a reflection geometry, the grating spacing is an order of magnitude smaller than in transmission. Thus, wavelength dispersion is typically about one to ten nanometers per degree, and even if a non-collimated polychromatic source is used, only a monochromatic image is seen. However, the narrow selectivity also means that to record multiple gratings, multiple writing wavelengths will be required. This is still a more prudent approach than multiple reading colors. Reflection also provides for a large viewing angle. The geometry of having the two beams incident from opposite sides allows the optics to be placed closer to the sample and thus can have a higher numerical aperture. Also, due to the fact that the reading light is not transmitted through the polymer for viewing, high absorption components can be used.

To be able to record a reflection grating with sufficient efficiency to be viewable, higher charge and trap densities will be necessary to accommodate the smaller grating spacing. This is not an easy task, though materials with internal diffraction efficiencies above 60% have been obtained [8, 9] with PVK-based devices. This polymer is not suitable for large area devices andhas a smaller hole mobility than the PATPD used here. Increased sensitization can improve trapping up to a certain concentration before the speed is reduced. Currently, a sample optimized for transmission would have a decreased write and erase time with lower efficiency when used in reflection.

A display with a write-erase cycle at video rates will require a pulsed laser at high repetition rate to deliver a large amount of energy in a short amount of time. This has the advantage of being insensitive to vibrations, a necessity for any practical application. A 1kHz repetition rate laser, used in the writing scheme employed here, can write a 4in x 4in display in just under 200ms, given the resolving power of the eye. This is not fast enough to give a seamless image, so other steps will need to be taken. Recording many hogels at once is possible with enough pulse energy, and improvements in the resolution of spatial light modulators will allow recording multiple hogels at once, or even direct recording of the interference pattern.Given the typical grating spacing, at least an order of magnitude decrease in pixel size is necessary.

Pulsed writing will also require a more sensitive material to generate as many charges as possible in the brief time the sample is illuminated. C_{60} has shown promise already in four-wave mixing [8] and preliminary display setups, though the sensitivity of PR polymers is still below that of chemical emulsions. Some novel techniques, such as quantum dots [10], buffer layers [11], and thermal fixing may be they key.

3. Conclusion

A large area photorefractive polymer has been developed for use in a 3D holographic display setup. The device demonstrates a writing time of a few minutes, persistency of hours, the ability to be erased at will, as well as phase stability. Further advances are required to realize the full potential of the holography. Material changes are needed for full color applications, and writing in the reflection geometry will be more practical. This approach also gives a wide viewing angle. Pulsed laser writing removes sensitivity to vibration and permits near video rate large area displays. All of these applications necessitate increased sensitivity and trap density maximize the benefit.

4. References

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