An Updatable Holographic Display for 3D Visualization

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(Invited Paper)

***Abstract*—Among the various methods to produce three-dimensional (3D) images, holography occupies a special niche. Indeed, holograms provide highly realistic 3D images with a large viewing angle capability without the need for special eyewear. Such characteristics make them valuable tools for a wide range of applications such as medical, industrial, military, and entertainment imaging. To be suitable for an updatable holographic display, a material needs to have a high diffraction efficiency, fast writing time, hours of image persistence, capability for rapid erasure, and the potential for large display area—a combination of properties that has not been realized before.**

Currently, there exist several media for recording holograms like photopolymers, silver halide films or dichromated gelatin, to name a few. However, in all of these media, the image is permanently written and cannot be refreshed. There also exist dynamic 3D display systems based on acousto-optic materials, liquid-crystals or microelectromechanical systems (MEMS), however they rely on massive wavefront computations that limit their image size capability. Inorganic crystals for hologram recording such as photorefractive crystals are extremely difficult to grow to larger than a few cubic centimeters in volume.Photorefractive polymers are dynamic holographic recording materials that allow for updating of images. They have been investigated over the last decade and have a wide range of applications including optical correlation, imaging through scattering media, and optical communication. Here, we report the details of the achievement of the first updatable holographic 3D display based on photorefractive polymers. With a 4×4 in^2 size, this is the largest photorefractive 3D display to date and is capable of recording and displaying new images every few minutes. The holograms can be viewed for several hours without the need for refreshing, and can be completely erased and updated whenever desired.

***Index Terms*—Holography, imaging, photorefractive materials.**

I. Introduction

THREE-DIMENSIONAL (3D) perception is a fundamental aspect of human vision. Our brain is accustomed to processing the tremendous amount of visual data presented to our eyes and rapidly retrieving relevant information, based upon parallax and depth perception among other visual phenomena.

Today's medical instruments, such as scanners, computer-aided tomography and magnetic resonance imaging (MRI) provide enormous amounts of 3D data. However, the visualization of the final information is limited by the bottleneck of the two-dimensional (2D) display. The end user, physician or surgeon, is always looking at a flat projection of what is, by nature, 3D information. Even though considerable research effort has been dedicated to the development of 3D imaging [1]–[9], we are still lacking an important interface between computer generated images and human perception.

Reconstructing 3D information has a long history, certainly as long as the art of painting for which perspective rules have been enacted. But it is only by understanding stereoscopic vision that modern science has been able to reproduce the impression of perspective.

From the early days of 3D rendering, stereoscopic devices relied on displaying different images to the left and right eye [3]. All such techniques suffer from the same drawbacks, namely that the viewer needs to wear special eye-wear or stand in a specific location for the 3D image to appear. The method by which the images are separated has evolved from the use of a separation fence between both eyes to prisms, mirrors, parallax barriers like Venetian blinds, colored filters in anaglyphs, polarization lenses or, more recently, time sharing using liquid crystal optical switches.

Holography clearly distinguishes itself from all the above-mentioned techniques. Indeed, it has the ability to reconstruct the wavefront of the light scattered by an object and thus reproduce the sensation of a viewer has standing in front of a real object [10]–[12]. No eyewear is required and different 3D views are perceived from different positions. Holograms do not just reproduce two images for stereoscopic purposes, rather they recreate all the view angles of the object within a certain view cone. This also means that the amount of information contained in an hologram is much larger than that in a simple stereoscopic device. With all of these unique properties, holography carries the potential to be the missing bridge between computer-processed 3D images and human perception.

Holograms can be permanently recorded in various media like silver halide films, dichromated gelatin or photopolymers. Surface relief holograms can even be imprinted on a wide variety of materials. Current static holographic displays are capable of displaying terabytes of data, and come at practically

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any size with full-color, full-parallax, and optical depth. However, until now, the recorded hologram could not be refreshed limiting usefulness for display applications [13].

Dynamic systems based on acousto-optic materials [14], [15], liquid-crystals [16] or microelectromechanical systems (MEMS)-based recording media [17] have been demonstrated. But, since these systems do not have memory they do not exhibit persistence for the recorded images and warrants update rates higher than 30 Hz to avoid image flicker. Since 3D images have very high information content, this high refresh rate requirement currently limits real time holographic displays to small sizes and low resolution.

Photorefractive (PR) crystals are dynamic holographic storage materials that exhibit memory [18]. However, they are currently only available in sizes of a few cubic centimeters and scaling them to the larger sizes needed for 3D displays is a significant challenge. Photothermoplastic materials provide reversible recording by utilizing surface relief gratings, but they suffer from limited diffraction efficiencies and usually require a post-recording developing process. To extend dynamic 3D holography to practical applications, larger displays made from alternative materials with high diffraction efficiency, write/erase capabilities and persistence are needed.

PR polymers are dynamic holographic recording materials capable of fulfilling these requirements. They have been extensively studied over the last decade [19]–[25] and have a wide range of applications including optical amplification [26], correlation [27], communication [28] and imaging through scattering media [29]. Large diffraction efficiency has been demonstrated [20] as well as high sensitivity and fast response time [30]. Well developed polymer chemistry and processing principles can be applied to provide large area, thin film display devices.

In a PR polymer, the light pattern created by two interfering coherent beams is replicated as a refractive index modulation or a phase hologram. This is achieved by charge generation in the illuminated areas, followed by transport and trapping in the dark regions. The spatial charge redistribution creates local electrical fields which orient nonlinear and/or birefringent molecules (chromophores) which in turn leads to a macroscopic refractive index change. Since the charge redistribution and molecular orientation is not permanent, this process is fully reversible and the recorded pattern can be erased by uniform illumination of the material. The record–erase (or read–write) cycle does not suffer from aging effects and a new hologram can be recorded in the same area.

In a typical read/write experiment, the hologram is recorded with two interfering coherent beams (object/reference) at a sensitive wavelength determined by the spectrum of the sensitizer molecule in the PR system. The reading can be done with monochromatic incoherent light at a wavelength far enough from the sensitizer spectrum that the grating is not erased due to uniform charge generation. The persistence time of the resulting hologram depends on material characteristics (self charge detrapping) and ambient temperature.

We have noticed from our previous studies that PR polymers that have fast recording time usually also have high decay rates [30]. However, for an updatable 3D display application, a material with rapid recording and slow decay (long persistence) is required. We define a figure-of-merit (FOM) for 3D displays as the ratio of the dark decay time (time for 50% reduction in diffraction efficiency) to half the recording time (time for 50% increase in efficiency) while the writing beams are turned on. In most PR materials we have studied in the past the FOM was close to unity, which is far smaller than the FOM of around 1000 required for use in updateable holographic displays with a large display area and high resolution.

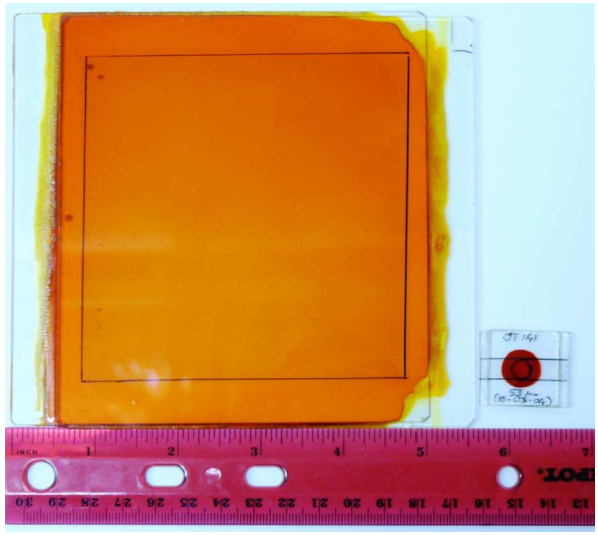

Fig. 1. A 4×4 inch^2 photorefractive sample next to a typical test sample.

II. Experimental Section

A. Material

We recently developed a PR polymer device with a fast response time and slow decay time $(\mathrm{FOM} > 1000)$ which together make it suitable for use in an updatable 3D displays [31]. The polymer composite consists of a copolymer with a hole-transporting moiety and a carbaldehyde aniline group (CAAN) attached through an alkoxy linker. The copolymer approach is adopted to minimize the phase separation between the functional components commonly seen in homopolymer PR composites while allowing larger chromophore doping concentrations. A copolymer with a polyacrylic backbone was used to attach pendant groups, tetraphenyldiaminobiphenyl-type (TPD) and CAAN in the ratio 10:1 by the synthetic modification of the polyacrylate TPD (PATPD) polymer [28]. The host PATPD-CAAN copolymer provides optical absorption and charge generation/transport at the writing wavelength (532 nm). A plasticizer, 9-ethyl carbazole (ECZ) was added to the composite. A large refractive index change was achieved by adding 30 wt% of fluorinated dicyanostyrene (FDCST) chromophore.

A composite of PATPD-CAAN:FDCST:ECZ (50:30:20 wt%) was formed into thin film devices by melting the composite between two transparent indium-tin-oxide-coated glass electrodes. Active layer thickness was set to 100 μm by using glass spacer beads. This composite showed no phase separation in an accelerated aging test at 60°C for 7 days. Fig. 1 shows a 4×4 in^2 active area thin-film device made from this composite next to a typical laboratory test sample. The device showed no degradation or dielectric breakdown for extended periods of use (several months) in our display setup, with hundreds of write/erase

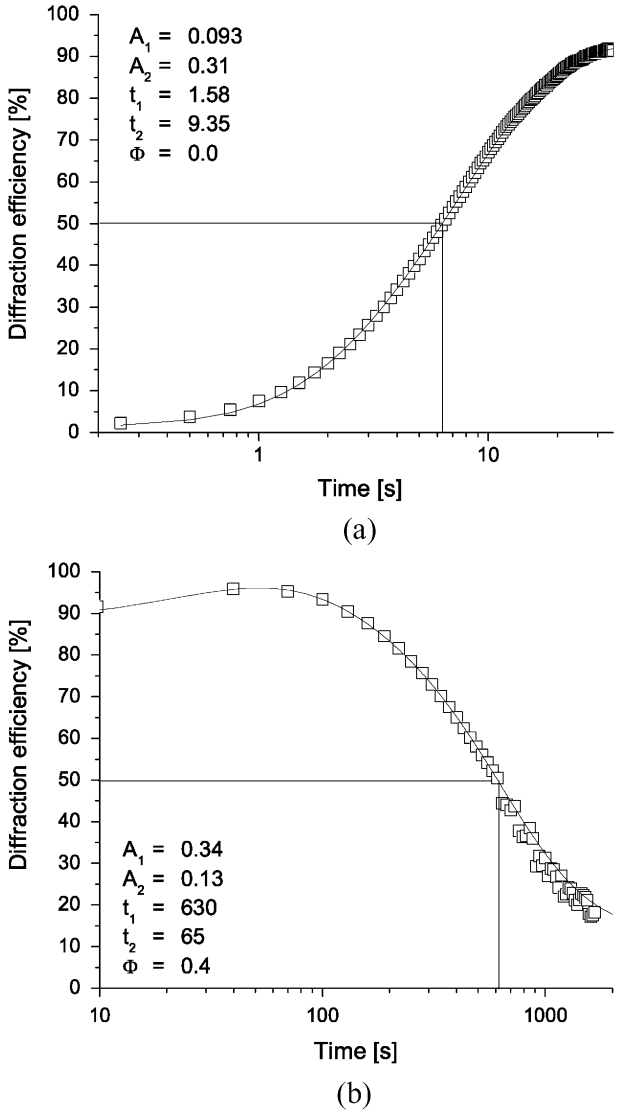

Fig. 2. Transient four wave mixing measurements at 5 kV. (a) Writing, (b) Dark decay.

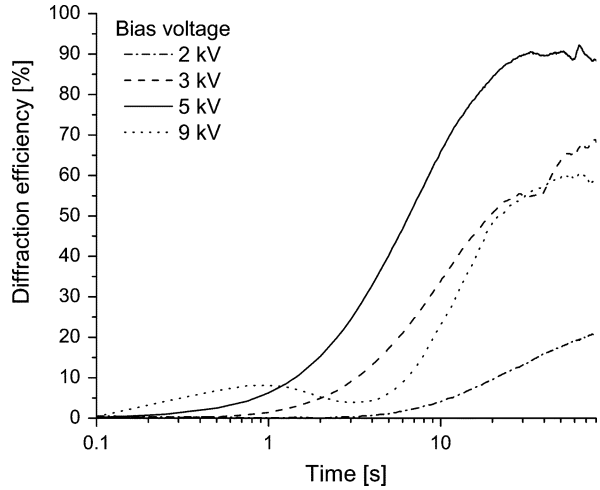

Fig. 3. Four wave mixing efficiency at different external applied voltage.

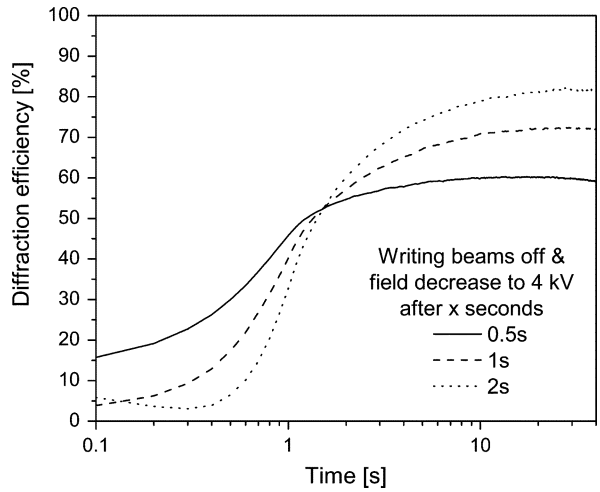

Fig. 4. Diffraction efficiency build up in the dark for various writing times. The writing time is defined as the time after which writing beams are switched off and the field is reduced from 9 to 4 kV.

cycles experienced at high applied voltages (9 kV) and writing optical intensities around 100 mW/cm^2.

The photorefractive thin-film devices show near-100% diffraction efficiency at an applied voltage of 5 kV in steady-state four-wave mixing measurements. The two-beam coupling gain coefficient Γ for these devices at 5 kV is around 200 cm^{-1}. Fig. 2 shows transient four wave mixing measurements along with the dark decay time for a writing optical intensitiy of 100 mW/cm^2 and an applied electric field of 5 kV. The diffraction efficiency η can be approximated by a sine square of a double exponential plus a phase parameter Φ:

$$\eta = \sin^2[A_1 \exp(-x/t_1) + A_2 \exp(-x/t_2) + \Phi] \quad (1)$$

Fitting parameters for each measurement are given in the Fig. 2 inset. Calculation of the 50% efficiency time is 6 s for writing, and 600 s for dark decay which yields a FOM of 100.

B. Voltage Kick-Off

A FOM of 100 with the writing parameters we used (intensity and voltage) is higher than for most reported photorefractive materials. However, this is not quite high enough for a display application, where an FOM value approaching 1000 is required.

Reducing the writing time by further increasing the writing beam intensity is limited by the laser source power and by sample optical and electrical damage. Another option is to modify both rise and decay times by changing the applied voltage: the larger the field, the smaller are the two times. Thus, it is possible to increase the FOM by writing at a higher voltage and reading at a lower voltage. The temporarily increased voltage during writing facilitates efficient separation of electron-hole pairs, and improves the drift characteristics, forcing the charges to travel faster, while also increasing the orientational order parameter and rotational speed of the chromophores. A reduction of the applied voltage immediately after recording ensures hologram persistence in the dark. We call this manipulation of the applied electric field "voltage kick-off".

However, Fig. 3 shows that the time to achieve 50% diffraction efficiency is reduced when increasing the applied voltage beyond a certain limit. After reaching an optimum value around 5 kV, the rise time for 50% efficiency increases again. Indeed, one can see that the first efficiency peak on the 9 kV curve in Fig. 3, observed around $t = 1$s, only reaches 8%. This reduced

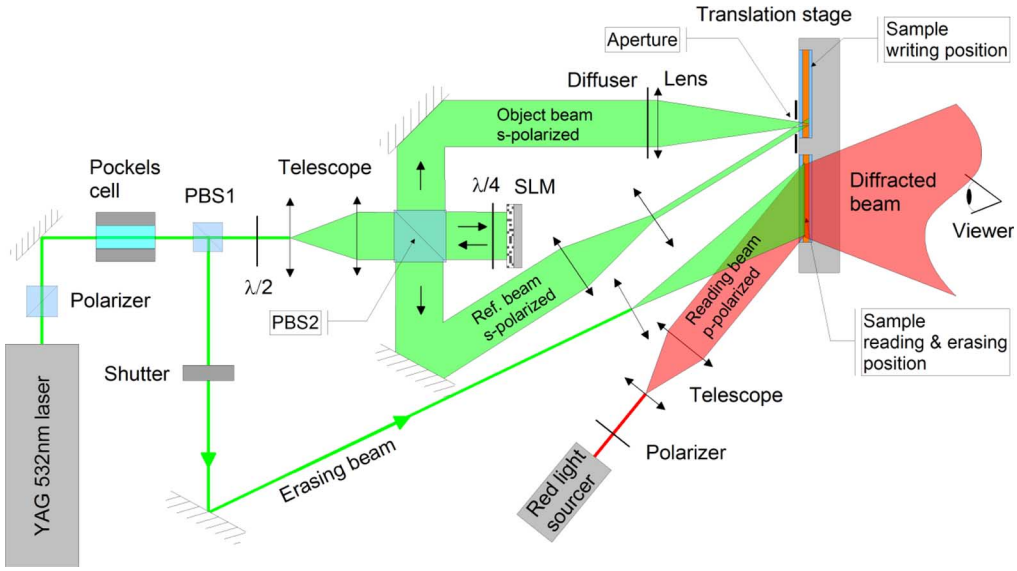

Fig. 5. 3D Display optical setup sketch. PBS: polarizing beam splitter; SLM: spatial light modulator; $\lambda/2$: half-wave plate; $\lambda/4$: quarter-wave plate.

value is due to the wide orientational distribution of the chromophore molecules during initial grating build up. Such a distribution is not taken into account in (1) and so this equation does not fit the experimental data.

We noticed that if the field is reduced *and* writing beams are turned off after that initial rise, the efficiency increases *in the dark*. (see Fig. 4). This behavior can be explained by the fact that the space charge field is fully established inside the material after a few seconds of writing but the chromophore molecules need more time to orient which can occur in the dark and at reduced applied field. This strategy of reducing the field and switching off the writing beams after the initial space-charge buildup allows a substantial increase in the previously defined FOM to the desired value of 1000 or more.

C. Display Setup

The display hologram is generated by holographic stereography [1], [32], [33]. This technique is based on optical multiplexing of a limited number of viewpoints of the same object (2D perspectives at different angles) onto different parts of a recording medium to recreate 3D perception along with parallax for the viewer during replay.

This powerful technique does not require the actual object to be present for recording. It can make use of data from any device capable of providing 2D perspectives of an object of interest. This means that methods like magnetic resonance imaging, computer-assisted tomography or echography, confocal microscopy, aerial and satellite 3D imaging, synthetic aperture radar, integral photography or computer assisted modeling can be used.

A sketch of the 3D display system we developed is presented in Fig. 5. The writing light source is a doubled YAG laser at 532 nm, a wavelength that is conveniently located within the absorption band of the PR material. The object beam is modulated with the holographic pixels (hogels) using a spatial light modulator (SLM). The object beam interferes at the sample position with a homogeneous reference beam in a Fourier transform geometry. These two beams are s-polarized to maximize the writing efficiency into the PR sample. A diffuser is used in the object beam path to homogenize the Fourier components at the focal point.

Writing is performed sequentially: the first hogel is recorded in the sample at the first location; next, the writing beams are turned off and the sample is moved to the second location where the second hogel is recorded. An aperture is used to help define the hogel position. Once all the hogels have been recorded, the sample is moved to the reading position.

Red light is used to display the hologram since sample absorption in that part of the spectrum is fairly low. This prevents charge generation and detrapping effects from erasing the hologram. We interchangeably used a red LED source (650 nm) or a HeNe laser (633 nm). LEDs possess the advantage of negligible speckle, owing to their low coherence, but using a rotating diffuser in conjunction with the laser is also effective. To maximize diffraction efficiency, the reading light should be p-polarized.

Hologram erasure is accomplished by illuminating the sample with a homogeneous beam at a wavelength which is within the absorption spectrum of the material. For the sake of convenience, we use part of the writing laser beam although there is no need for coherence.

The system we built is for a horizontal parallax only (HPO) holograms. We used cylindrical lenses for shaping the object and reference beams, such that each hogel is a vertical strip. In many applications, HPO imaging is an effective approximation of 3D representation because humans perceive depth using the horizontally offset eyes. HPO reduces the number of hogels required to write the full hologram by the square root of the area, thereby reducing the overall recording time. It has to be noted that our technique is scalable to full parallax.

III. Results and Discussion

We have recorded HPO holograms 4×4 inch^2 in size with complex and high-quality images (see Fig. 6). The recording time used per hogel (0.83 mm width) was varied from 0.5 to 2 s depending upon the desired diffraction efficiency and persistence time. Since there are 120 hogels to be recorded per holo-

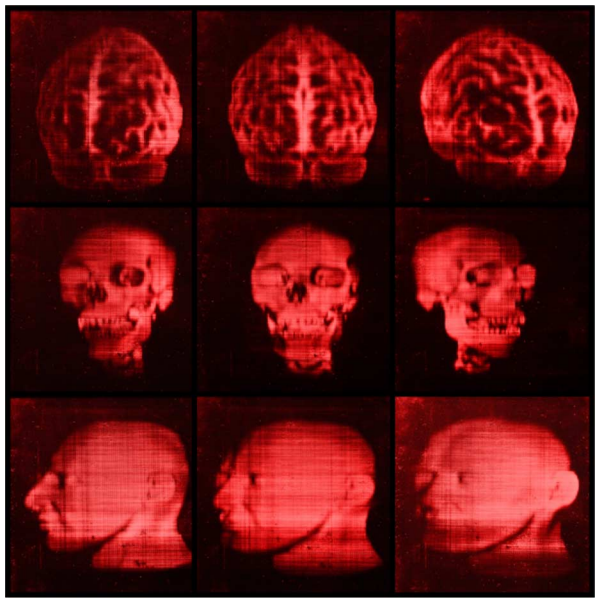

Fig. 6. Images captured from the updatable holographic 3D display. In a single row, the camera is moved sideways to show parallax: rotation and occlusion. 3D image is erased and a new set of data is recorded in the same location between rows.

gram, the total recording time varied from 1 to 4 min. Total irradiance (sum of both writing beams) used was 100 mW/cm^2.

For the 3D display application, we used a modified version of the voltage kick-off technique presented in the above section. Here, a constant high voltage (9 kV) is applied to the entire polymer device during hogel recording. Once all of the hogels are recorded, which takes around 2.5 min, the voltage is reduced to its optimal value of 4 kV. This ensures long persistence of the hologram with maximum diffraction efficiency. The first few recorded hogels suffer a small reduction of diffraction efficiency due to the higher applied voltage during recording of the later hogels, but this lower diffraction efficiency does not create any noticeable brightness variation across the display. For larger displays the variation may be significant, but this can be avoided by the use of patterned electrodes that allow individual control of the applied voltage for each hogel or group of hogels.

Our 3D display features a total horizontal viewing angle of 45° with uniform brightness. This viewing angle is defined by the f-number of the last focusing lens in the object beam path. The images are viewable for up to 3 hours directly on the photorefractive thin-film device without the need for intermediate projection tools or magnification between the recorded image and the viewer.

The hologram can be completely erased within minutes by uniform illumination of the display using the erasure procedure discussed above. New images can be recorded when desired.

The snapshots of the holograms presented in Fig. 6, which were captured using a CCD camera, are only a modest reproduction of the effect actually experienced upon direct viewing. This is principally due to the astigmatism introduced by the HPO recording technique and electronic artifacts such as saturation, to which the human visual system is relatively insensitive.

We do not anticipate any practical technological limit on the achievable display size: large devices can be fabricated and/or tiled together and the plastics industry has already shown the ability to laminate extremely large multi-layer thin-films. Moreover, the persistence and diffraction efficiency of the material make it a leading candidate for future full-parallax displays, which typically require two orders of magnitude more information content than HPO displays. For larger, full-parallax displays a combination of short pulse recording [30] and thermal fixing [34] can be used, which are future areas of research for holographic 3D display development. Color rendering can also be implemented if we trade off the reading time and the intensity of the green and blue reading beams which generate charges that can erase the hologram.

In summary, we have developed PR polymer devices that combine exceptional properties such as large size, high efficiency, fast recording, image persistence, long lifetime and resistance to optical and electrical damage, satisfying many of the major requirements for use in holographic 3D displays. These advances have allowed us to demonstrate the largest updatable photorefractive holographic 3D display to date. Holographic image-updating capability can significantly extend the applications of 3D displays in the fields of entertainment, education, medical and technical imaging, either civilian or military.

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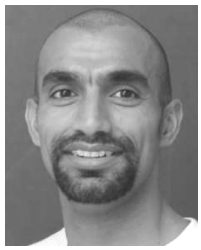
His graduate research involved several topics in nonlinear optics, photonics and holography. He is currently a Post-Doctoral associate at the Bioengineering Department at Stanford University and Howard Hughes Medical Institute where he is working on stem cells and systems biology using microfluidics.



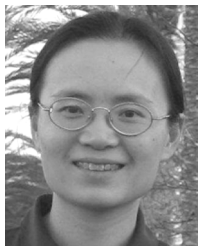
Ram Voorakaranam received the M.E. degree in systems science and automation from the Indian Institute of Science, Bangalore, India, in 1996 and the Ph.D. degree in electrical engineering from the Georgia Institute of Technology, Atlanta, in 2002.

From 2000 to 2006, he worked in the semiconductor industry building hardware and software solutions for production testing of precision analog products, mixed-signal and RF integrated circuits, and developing fast test algorithms and methodologies for volume production testing on low-cost test platforms. Since 2006, he has been with the Photonics and Lasers group at the College of Optical Sciences, University of Arizona, Tucson, where he is involved in the development of electro-optic modulators, magneto-optic sensors, and holographic displays.

Pierre Saint-Hilaire received the the B.Sc. degree in engineering physics from the Ecole Polytechnique de Montreal (Canada), in , the M..Sc. degree in physics from McGill University, Montreal, Canada, in , and the M.Sc. and Ph.D. degrees in media technology from Massachusetts Institute of Technology, in .

He is currently adjunct professor at the College of Optical Sciences, University of Arizona, Tucson. His areas of interest include holography, fiber Bragg gratings, and display technology.

Cory Christenson received the B.A. degree in physics from Gustavus Adolphus College, in 2005. He is now pworking toward the Ph.D. degree in physics at the College of Optical Sciences, University of Arizona, Tucson.



Tao Gu received the B.S. and Ph.D. degrees from the Zhejiang University, Hangzhou, China.

From 1999 to 2001, she worked as a Post-Doctoral with Dr. J.-F. Nierengarten at the Institut de Physique et Chimie des Materiaux de Strasbourg and Louis Pasteur University, Strasbourg, France, specializing the synthesis of new conjugated organic materials for solar cells. Her postdoctoral work at the North Carolina State University and the University of California at San Diego in the group of Dr. Marye Anne Fox and Dr. James K. Whitesell involved photoinduced energy/charge transfer on nanostructured systems such as nanoparticles and dendrimer complexes. From 2005, she is Chief Researcher at the Nitto Denko Technical Corporation, Oceanside, CA, where she is working on photorefractive materials.

Weiping Lin received the M.S. degree in optics from Shanghai Institute of Optics & Fine Mechanics, Shanghai, China, in 1983.

Following his degree, he continued to worked at Shanghai Institute of Optics & Fine Mechanics, Shanghai, China, till 1988. He was a visiting scholar at Brown University, Providence, RI, from 1988 to 1989, and at Northwestern University, Chicago, IL, from 1990 to 1995. From 1995 to 2005 he worked at IPITEK Corporation, Carlsbad, CA, as a Staff Engineer and was engaged in the R&D and fabrication of polymer electro-optic modulators. Since 2005, he has been with Nitto Denko Technical Corporation, Oceanside, CA, where he has been working on study of polymer nonlinear optical materials and research and fabrication of holographic display devices.

Donald Flores received the B.S. degree in chemical engineering from the University of California, Riverside, in 2006; receiving his E.I.T. license that same year.

From 2005 to 2006 he worked with Dr. Y. Yan at the Bourns College of Engineering, University of California, Riverside, performing scale-up synthesis of and characterization studies on Zeolite coatings. Since 2006, he has been with Nitto Denko Technical Corporation, Oceanside, CA, as a Researcher, working on photorefractive materials.

Peng Wang received the B.S. degree from the University of Sciences and Technology of China in 1993. Following his degree, he joined the Institute of Chemistry, the Chinese Academy of Sciences as an assistant researcher and received the M.S. and Ph.D. degree on nonlinear optical materials from the same institute.

Since 2001, he has been with Nitto Denko Technical Corporation, Oceanside, CA, as a chief researcher. His principle research activities are organic photorefractive materials and their holographic applications.

Michiharu Yamamoto receives the M.S. degree from Osaka University, Osaka, Japan, in organic chemistry (1995). He then joined Nitto Denko Company, Ltd., in 1995; he moved to Nitto Denko Technical "Organic polymer material studies" in 2000, where he is currently the Director.

Jayan Thomas received the Ph.D. degree in material science from Cochin University of Science and Technology, Kochi, India, in 1996, with a prestigious Dr. K. S. Krishnan fellowship.

After working as a research associate at the International School of Photonics, Cochin University of Science and Technology, Kochi, India, in 2001, he joined the College of Optical Sciences, University of Arizona, Tucson, where he is currently an Assistant Research Professor. His current research interests include photorefractive polymers, nonlinear optical materials, magneto-optic materials, nanoimprinting techniques, optical limiting devices, photonic crystals, nanoarchitectured solar cells, nanostructured Li-ion batteries and supercapacitors. He has served as a reviewer for several scientific journals and published about 50 scientific papers and a book chapter on photorefractive polymers.

Dr. Thomas is a member of the American Association of Advancement of Science (AAAS). His professional activities include organizing SPIE Conference on Linear and Nonlinear Optics of Organic Materials.

Robert A. Norwood received the B.S. degree in physics and mathematics from the Massachusetts Institute of Technology, Cambridge, in 1983, and the Ph.D. degree in physics from the University of Pennsylvania, Philadelphia, in 1988.

Since 2004, he has been a Research Professor in the College of Optical Sciences, University of Arizona, Tucson, where he performs research on high speed electro-optic modulators, integrated magneto-optic devices, 3-D display technology, photonic crystal techniques and devices, and ultrafast optical switching. He was Vice President and CTO at Photon-X (1999–2004), a photonics company based in Malvern, PA. He led R&D groups at AlliedSignal (Honeywell) and Hoechst Celanese; the group at AlliedSignal (1995–1999) developed aerospace qualified polymer waveguide technology that was the best in the world at the time. At Hoechst Celanese (1988–1995) he performed and led research on waveguide frequency doubling, third-order NLO materials, optical limiting, coatings for photolithography, and sol-gel passivation layers, and helped to setup an advanced electronic/photonic materials laboratory at Hoechst Japan. He is an expert in polymer integrated optics and optical materials with 41 refereed publications, 5 book chapters, 25 issued U.S. patents, and 42 invited talks.

Dr. Norwood is a fellow of both Optical Society of America (OSA)and SPIE, as well as a member of the American Physical Society (APS).

Nasser Peyghambarian received the Ph.D. degree in solid-state physics from Indiana University, W. Lafayette, in 1982, specializing in optical properties of semiconductors.

He worked as a postdoctoral fellow at Indiana University from 1981 to 1982 and the Optical Sciences Center, University of Arizona, Tucson, from 1982 to 1983. He is currently a Professor at both the College of Optical Sciences and the Department of Materials Science & Engineering at the University of Arizona, Tucson. He is also Chair of Photonics and Lasers at the University of Arizona as well as Director of the Photonics Initiative. He is the Founder of TIPD, LLC. He is Chairman of the Board and Founder of NP Photonics, Inc. His research interests include optical components for communication, waveguide and fiber optics including fiber lasers and amplifiers, passive optical components, such as splitters, combiners, arrayed waveguide gratings, glass-organic hybrid materials and devices, organic light emitting diodes, organic lasers, plastic optoelectronics, photorefractive polymers, sol gel components, nonlinear photonics and photonic switching, laser spectroscopy of semiconductors using femtosecond light pulses, semiconductor quantum dot and quantum well research.

Dr. Peyghambarian is the recipient of the University of Arizona's 2007 Technology Innovation Award, International Francqui Chair, Belgium 1998–1999, TRW Young Faculty Award, and 3M Company's Young Faculty Award. He is a Fellow of the American Association for the Advancement of Science, the Optical Society of America (OSA), the Society for optical engineers (SPIE), and the American Physical Society (APS).