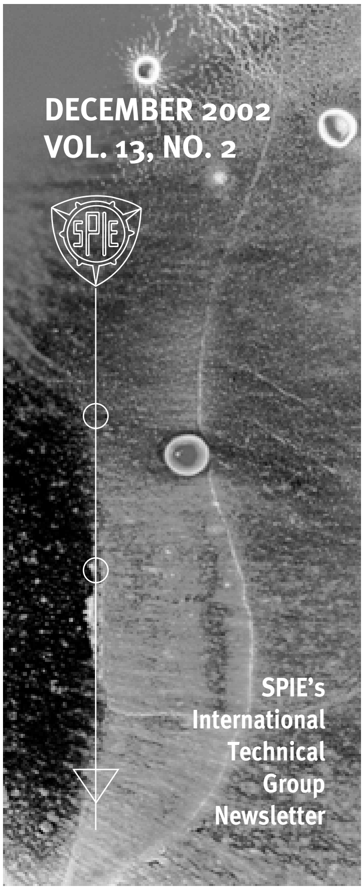

HOLOGRAPHY

Additive lithography for micro-optic fabrication

Diffractive and refractive micro-optics have revolutionized the photonics industry due to their wide range of applications and their high-volume wafer-scale production potential. However, the present range of applications is severely limited by our ability to fabricate complex profiles on an optical substrate with high precision. A number of different techniques exist for the fabrication of multi-level diffractive optical elements (DOEs). However, we have recently developed an innovative method that uses varying exposure times and masks to sculpt complex photoresist profiles across the wafer substrate. This method, termed *additive lithography*, avoids some of the drawbacks of other fabrication methods and has allowed us to form various types of DOEs and refractive microlens arrays with much lower production costs, and without requiring compromises on tolerances.

The primary fabrication methods currently in widespread use involve either gray-scale or binary amplitude masks. The binary mask process suffers from the necessity of using a number of different masks, each requiring a separate sequence of photoresist coating, mask aligning, patterning, and etching. This involves a long and difficult process made ever-more difficult by the complexities of precisely aligning subsequent masks.[2] Gray-scale masks avoid many of these difficulties and provide many additional benefits. However, gray-scale mask technologies are typically highly spe-

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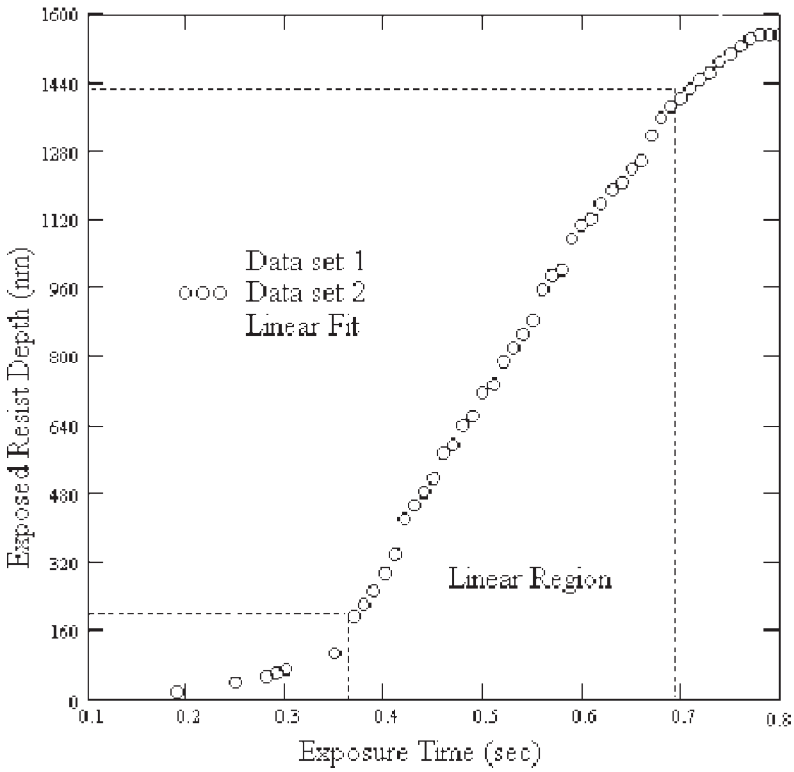

Figure 1. Depth versus exposure time with a linear fit.

Technical Group Registration Form—*See page 11*

Newsletter now available on-line

Technical Group members are being offered the option of receiving the Holography Newsletter electronically. An e-mail is being sent to all group members with advice of the web location for this issue, and asking members to choose between the electronic and printed version for future issues. If you are a member and have not yet received this message, then SPIE does not have your correct e-mail address.

To receive future issues electronically please send your e-mail address to:

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with the word `holography` in the subject line of the message and the words `electronic version` in the body of the message.

If you prefer to receive the newsletter in the printed format, but want to send your correct e-mail address for our database, include the words `print version preferred` in the body of your message.

An update on commercial recording materials

The most common materials used for recording holograms are silver halide, dichromated gelatin, photopolymer, photoresist, thermoplastic, bacteriorhodopsin, and photorefractive. Over the last few years some companies have stopped manufacturing materials and new ones have appeared on the market. An update of current suppliers of holographic materials may therefore be of interest. In the article that follows, we go through each area, briefly, in turn, with a summary of most of the current commercial holographic recording materials listed in Table 1, and contact information for most of the suppliers mentioned listed alphabetically at the end. More details about some of the materials mentioned here may also appear in future newsletters.

Commercial silver-halide emulsions

- Today, the main manufacturer of holographic silver-halide emulsions is the Micron branch of the *SLAVICH Joint Stock Company*, a photographic company located outside Moscow. They manufacture both film (triacetate) and glass plates. Many different sizes are produced, including 115×10m film rolls.
- *Colourholographic Ltd.* is a new company based in England. The Colourholographic materials are based on the HRT emulsion, previously manufactured in Germany by Dr. Birenheide. At the present time only glass plates are manufactured in England.
- *Eastman Kodak's* holographic materials are produced in America. These plates are usually made to order only. Materials can be ordered with (marked -01) or without (marked -02) anti-halation layer. The 120 emulsion can be used for recording holograms using a pulsed ruby laser. **NB: KODAK has announced that they will cease the manufacture of emulsions coated on glass plates at the end of 2002.**
- *FilmoTec* is located in Germany. The company manufactures ORWO holographic emulsions which are coated only on triacetate film, 104cm wide in 10m and 30m lengths.
- In France, Yves Gentet has started a small-scale emulsion manufacturing company: *Atelier de Création d'Art en Holographie Yves Gentet.* Monochromatic and panchromatic ultrafine-grain emulsions are produced called *Ultimate*. Plates and film up to 60×80cm are produced.
- *Agfa* is still manufacturing the lithographic green-sensitive *MILLIMASK* high-resolution emulsion. This product can replace the former Agfa *HOLOTEST 8E56* holographic plates. However, Agfa may also stop the production of this emulsion. Currently, the *MILLIMASK* plates can only be ordered from *Micro-chrome Technology Inc.* in the USA.
- *Konica* in Japan is manufacturing a green-sensitive emulsion for the use in the American VOXEL 3D medical imaging system and for the Japanese market only.

Table 1. Summary of commercially-available holographic recording materials.

Material		Thickness [µm]	Spectral sensitivity [nm]	Sensitivity [µJ/cm²] at 442	514	633	694	Resolving power [lp/mm]	Grain size [nm]
SILVER HALIDE EMULSIONS									
Slavich									
Red	PFG-01	7	<700			80		>3000	35-40
Red	PFG-03M	7	<700			1500		>5000	10-20
Green	VRP-M	7	<550		80			>3000	35-40
Pan	PFG-03C	9	400-700	2000	3000	1500		>5000	10-20
Colourholographic									
Red	BB-700	7	<700			50	150	>2500	50-60
Red	BB-640	7	<650			150		>4000	20-25
Green	BB-520	7	<540	150	150			>4000	20-25
Blue	BB-450	7	<470	150	-	-	-	>4000	20-25
Kodak									
Red	131PX	9	<650	5	-	0.5	-	>1250	70
Red	131CX	9	<650	5	-	0.5	-	>1250	70
Red	120PX	6	<750	6	-	40	40	>2500	58
Red	120CX	6	<750	6	-	40	40	>2500	58
FilmoTec - ORWO									
Red	HF 65	10	<650			1500		5000	30
Green	HF 53	10	<550		700			5000	30
Ultimate									
Ultimate 15		7	<700	-	150	150	150	>5000	15
Ultimate 08		7	<650	120	200	200	-	>7000	8
DICHROMATED GELATIN EMULSIONS									
Slavich									
Blue	PFG-04	16	<515	100	2x10^5	-	-	5000	-
FilmoTec - ORWO									
Blue	GF 40	6/20*	-	-					-
*delivered unsensitized									
THERMOPLASTIC MATERIALS									
Tavex America									
Pan	TCC-2	-	<800	1			1	1500	-
PHOTORESIST MATERIALS									
Towne Technologies									
UV-Blue	Shipley 1800	1.5-2.4	<450	1.5x10^5				1000	-
Hoya Corporation									
Custom-made only									
BACTERIORHODOPSIN MATERIALS									
MIB GmbH									
BR-WT B-type		30-100	<650	-	80,000	-	-	5000	
BR-D96N M-type		30-100	<650	30,000	-	-	-	5000	-

Commercial DCG materials

- *Slavich* in Russia is one manufacturer of presen-sitized dichromated plates for holography. The DCG emulsion is marked PFG-04. Plates up to a size of 30×40cm can be ordered.
- The *FilmoTec* DCG emulsions are only available on 190µm triacetate film, 104cm wide in 10 and 30m lengths. Emulsion thickness 6 or 20µm. Note that the film needs to be sensitized in dichromate solution before recording. This means that the company only supply large-format gelatin-coated film.
- *Holotec* is a German-based company which offers presensitized DCG coated on both plates and film. Holotec uses the high-quality DCG emulsions developed by Professor Stojanoff in Aachen. The company can supply large-format DCG glass plates (m^2 size) or film (PET-Polyethylenterephtalat), presensitized and ready to use.

Commercial photopolymer materials

- Currently the main and only manufacturer

Continues on page 10.

Optical test alignment using computer-generated holograms

Measurement systems for optical surfaces and systems that lack axisymmetry are notoriously difficult to align and have limited accuracy. We describe a technique that uses a single computer generated hologram (CGH) to act as null lens for measuring the aspheric surface, at the same time as it projects alignment marks into space that can be used for aligning the test. By providing reference features and the surface shape on the same hologram, we ensure accurate alignment. This method can also be used for aligning systems with multiple surfaces.

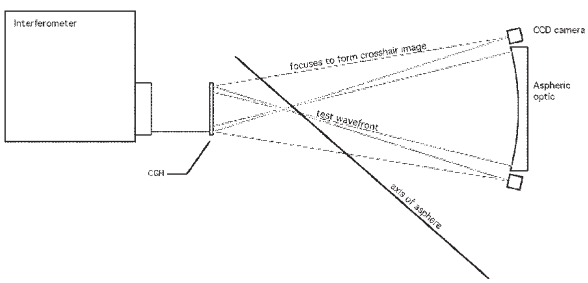

Figure 1. A single substrate contains the CGH for testing the aspheric surface and for aligning the test. The alignment marks are picked up by CCD cameras and are used to define the coordinates of the optic. The surface is measured using the test wavefront created by the CGH. The registration between these ensures that the true axis of the asphere is controlled, even though it is never directly measured.

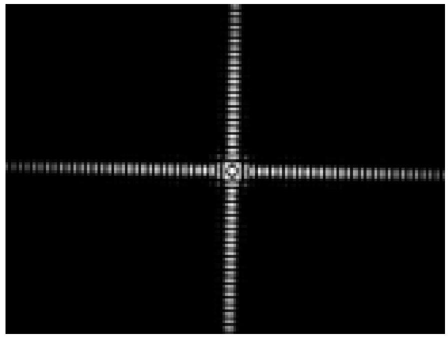

Figure 3. Digitized image of the alignment mark for aligning the off axis paraboloidal mirrors. The FWHM of the central lobe is 100 micrometers.

The CGH provides a well-known tool for controlling light for interferometric measurement of aspheric surfaces and for dividing light into multiple beams. It uses diffraction from a pattern fabricated onto an optical substrate to create a wavefront with arbitrary shape. The patterns are determined by computer simulation and they are written onto the substrate using equipment developed for integrated circuit fabrication.

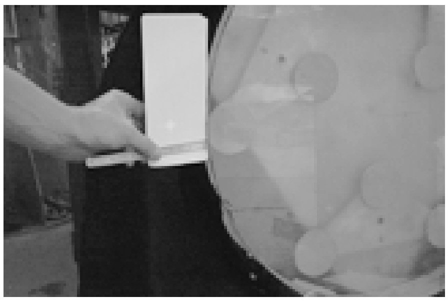

Figure 2. Optical test of a 60cm aspheric optic, showing one of the alignment marks that was used for alignment. The distance from the alignment mark to the edge of the glass was used for alignment.

Figure 4. Measurement of the 60 cm aspheric surface showing l/20 residual shape errors.

We are combining aspects of CGH metrology and beamsplitting to create holograms that produce multiple wavefronts that have accurate registration. Using a combination of interferometry and direct imaging, the light projected from a CGH can be used not only to determine the shape of an optical surface, but to also, simultaneously, determine its position. This technique can be extended to control the relative positions of multiple surfaces.

The basic idea is shown in Figure 1, where a single CGH is placed in front of an interferometer and creates multiple images. The center of the CGH pattern is used as a diffractive null lens for testing an off-axis aspheric surface. The outer regions of the CGH are used to project crosshair patterns that enable alignment. The positions of these patterns can be found to a few microns using a CCD camera.

This method was successfully applied for measuring 60cm diameter paraboloidal mirrors with optical axes 1.5m from the center of the part (the parent asphere would be over 3m in diameter.) A CGH was manufactured for this application and was mounted to a phase-shifting interferometer. The paraboloidal mirror was then supported 15m away.

Four alignment marks were projected to the edge of the part, as can be seen in Figure 2. This image was captured digitally using a CCD camera to give accurate position information. A digitized image is shown in Figure 3. The light reflected back into the interferometer was used to measure the optical surface, giving results shown in Figure 4. The test was aligned by controlling the positions of the alignment marks, relative to the edge of the blank.

In addition, we performed a controlled set of experiments to verify the accuracy of the method. We used CGHs to create multiple alignment patterns in desired locations over distances up to 1.6m. We located these positions using a calibrated CCD and careful mechanical measurements to an accuracy of about 10µm.

This same technique of multiplexing multiple holograms on the same substrate can be used for other applications, including providing alignment references for multi-degree-of-freedom surfaces. The light from the CGH can be controlled so it comes to focus in any intermediate optical space. Also, the holograms can define degrees of freedom in combination with low-order wavefront sensing. Particular images that have characteristic signatures for different aberrations can be used to determine alignment. One simple example would be a pair of images with a small amount of defocus between them. The combination of these two images can be used to determine aberrations in the optical system. These can provide feedback for the system alignment. The enormous power and flexibility of this method is now being explored.

We acknowledge the contribution of Vadim Cherkashin. He developed the algorithms and software for manufacturing the test holograms using a circular laser writer.

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Interferometry with high-resolution materials based on bacteriorhodopsin films and a novel holographic camera

When holographic interferometry was developed in the ’70s and ’80s, it was embraced as promising new tool to obtain information about surfaces of objects under different conditions. Surface changes accessible by holographic interferometry may be as small as the wavelength of light employed to record the image. The resolution of the holographic image, however, is limited by the resolution of the recording material. For a long time, the only suitable recording materials commercially available for holographic interferometry were based high-resolution silver-halide films. Partially due to the fact that these media require wet chemical processing, holographic interferometry never found widespread application in fields where a high throughput of image data is required (e.g., industrial production and quality control).

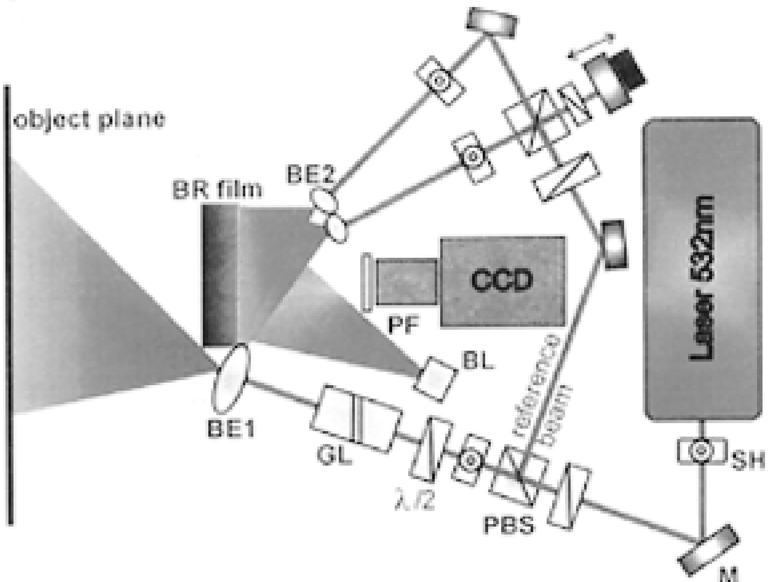

Figure 1. Shown is a simplified setup of our holographic camera. The polarizing beam splitter (PBS) splits the laserbeam into two parts: reference and object beam. The reference beam, which can be shifted by a piezo driver, is expanded by BE2 and illuminates the BR-film on the rear side. Back-scattered laser light from the object illuminates the BR-film on the front side. Polarizing beamsplitters, together with half-wave plates, are used to adjust the object/reference ratio.

Recent advances in charge-coupled device (CCD) cameras have provided us with an alternative way to record and temporarily store images. Although this approach avoids the need for wet chemical processing, it still has a number of limitations with regard to holographic applications, the main one being that CCD chips can only record very low spatial frequencies (depending on their pixel size) and so only small angles between object and reference beams can be used.

Electronic Speckle Pattern Interferometry (ESPI) was developed based on this CCD technology. Here, the angle between object and reference beams can be set to zero, and speckles generated are recorded together with phase-shift information. When employing arctan calculations, information about object movements of the order of l/10 can be obtained. The spatial resolution of images generated by ESPI depends on the speckle size and the size of the pixels, convolved with the resolution of the imaging optics used. As a result, a typical resolution of the order of a fraction of a millimeter can be achieved.

Holographic recording materials based on bacteriorhodopsin

Bacteriorhodopsin (BR) is a biological photochromic dye with exceptional properties that can be used to record images. Exposure of optical BR films to green light (e.g. a frequency-doubled Nd:YAG laser) instantaneously generates a yellow image in the originally-purple film. Blue light erases the image and a new image can be acquired without a time delay. Several million write/erase cycles are possible. The sensitivity of a typical BR-film is suitable to generate full holographic modulation with 100μJ of light. Holographic efficiency is up to 4% in phase and amplitude mode, enough for bright hologram reconstruction. A very-high signal/noise ratio can be achieved in polarization mode. BR films show very high resolution of more than 5000 lines/mm in holographic experiments.[1]

High-resolution optical recording materials based on BR are exceptional storage media for the amplitude and phase information of holographic images. BR films do not exhibit the limitations of conventional films nor of typical CCD cameras. BR films can be used as instant holographic recording media with no further chemical, thermal or electrical processing required. Immediately after exposure, the hologram is finished and can be analyzed. In BR films available from MIB GmbH,[2] BR molecules are embedded into a gelatin matrix between glass plates. These films can be used like conventional photographic plates.

The holographic camera

The exceptional properties of BR films can be used best in conjunction with an instant holographic camera for high-resolution holographic measurements of small movements and vibrations in objects.[3] Since BR films do not exhibit changes in film properties like swelling or shrinking, Denisyuk-type holograms can be used. As a result, a compact measurement system is possible (Figure 1) where the reference beam is directed to one side, the object beam to the other side of the BR-film.

Light from a frequency-doubled Nd:YAG laser illuminates the object being tested, and light scattered by this object illuminates the BR-film. Light from the same laser source, which is expanded by microscope objectives, is used to illuminate the BR-film from the opposite side to form a side-band Lippmann hologram. One deflection mirror is mounted on a piezo driver, so that a phase shift between object and reference beam can be realized. As a result, an out-of-plane resolution of better than l/100 can be achieved in this configuration. Due to the high resolution of the recording material, the spatial resolution of this holographic camera (in the plane of the BR-film) is significantly better than that typically found in ESPI systems.

The hologram generated by the camera can be reconstructed immediately after exposure, so real-time and time-averaged holography are the preferred measurement applications. Object movements can be obtained in real-time mode to detect static as well as dynamic deformations in the sub-micrometer range. Phase shifting and image recording with an auxiliary CCD camera connected to a computer allows

Continued on page 6.

Holographic optical elements for window shading in buildings

Shading devices, air conditioning systems, or a combination of both are used to prevent overheating in buildings during the summer. Contemporary high-rise buildings particularly require efficient cooling as they are frequently constructed with glass envelopes. Architects use a variety of shading devices to prevent such overheating. One of these is the conventional venetian blind, which has the disadvantage of also blocking sunlight: thus artificial light is needed to illuminate the room. Other shading devices may be installed outside the building at a certain angle to block direct sunlight. The latter solution has the disadvantage of substantially increasing construction costs. Some modern glasses and films that exhibit reduced heat transfer are also used as shading devices. In principle, these glasses are designed to reduce the amount of radiant energy penetrating the building envelope. Thus, they may again require artificial lighting for illumination. Finally, the active cooling of buildings by means of vapor compression units or absorption refrigeration requires large amounts of energy and complex control strategies.

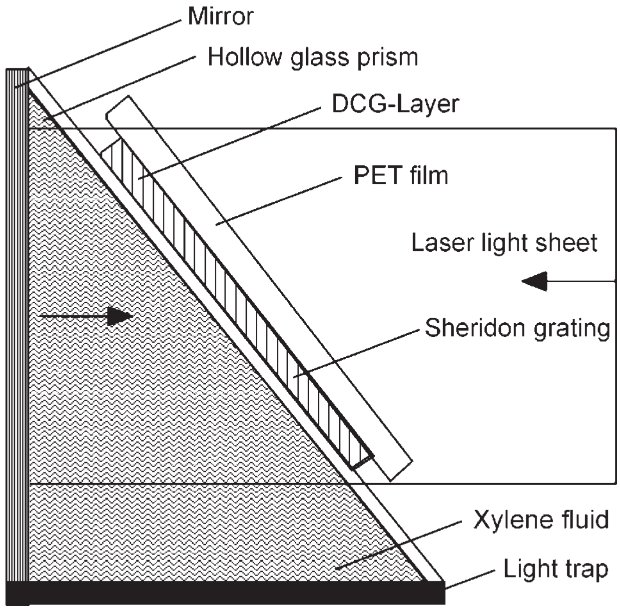

Figure 1. Sheridon-grating recording geometry.

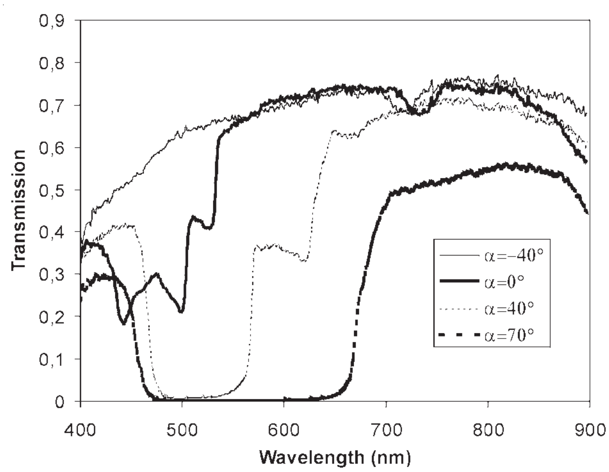

Figure 2. Spectral transmission of 2D-shading hologram for various angles of incidence.

A passive strategy for creating comfortable working or living conditions in a building is clearly preferable. We report here the development of a novel shading device that uses reflection holograms to selectively block solar radiation. This holographic shading device (HSD) works at a pre-selected central wavelength and possesses a spectral bandwidth that may be adjusted to meet design requirements. The efficiency of the HSD is a function of the reconstruction angle. The angle at which the HSD exhibits the maximum of the diffraction efficiency—the Bragg-angle—may be adjusted through the selection of the recording geometry. In this way the HSD blocks the sunlight only at certain positions of the sun: for example at noon during summer, i.e., when the cooling is usually needed. The hologram is transparent for other positions of the sun or for diffuse radiation.

Two types of reflection holograms may be used for glazing in buildings or as sun protection. The holograms are designed in such a way as to pass the solar radiation in the winter (angle of incidence 20° to 40°) and block it in the summer (angle of incidence 40° to 70°). A reconstruction angle of 0° represents the transmission for an observer looking along the normal vector of the windowpane. All angles are specified with respect to the normal vector of the window aperture. These parameters are typical for central Europe. The angular selectivity may be adapted for any region in the world by selecting the appropriate angles.

The first device is designed as a venetian blinds structure with the lamellae positioned at 45°. The blinds are made of holograms on glass substrata—one red and one blue—that are pasted together. The relevant information on the design procedures and the performance tests are given in previous SPIE publications.[1, 2] The structure is three-dimensional, and avoids the use of mechanical adjustments.

The shading device discussed above has the disadvantage of being bulky and coloring the room. For this reason we developed a new two-dimensional shading system that consists of a single holographic layer on a glass or plastic substrate to facilitate integration with the window pane (safety glass structure). The hologram is designed as an asymmetric reflection hologram (Sheridon grating[3]).

The recording procedure is depicted in Figure 1. The current recording method limits the height of the hologram to 40cm due to beam divergence at larger distances between the hologram and the mirror. Shading holograms are recorded in 12 -18μm dichromated gelatin (DCG) layers on glass substrata and are currently 30cm ×1m, but the method we use for DCG film coating permits the making of holographic films on glass substrata to a length of 2m. The hologram is fabricated on flexible PET film using a continuous, automated process. The width of the existing machine for the coating of endless holographic films on flexible substrata is limited to 22cm, and is currently run at 20cm.

The advantage of the shading hologram is that the view through the window is unobstructed by color stripes as is the case with venetian blinds. The transmission characteristics for a test hologram are depicted in Figure 2. The angles are defined with respect to the window's normal vector. As a result, negative angles indicate that the observer is looking downward from the window.

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Interferometry with high-resolution materials based on bacteriorhodopsin films and a novel holographic camera

Continued from page 4.

the determination of phase signs so that the direction and the absolute value of the deformation can be calculated.

Experimental results

The following experiments demonstrate some properties of the camera system. A circular metal plate (bronze, thickness 0.15mm, diameter 100mm) was mounted in front of a loudspeaker, without a diaphragm, so that only the coil of the loudspeaker would drive the plate. With this set-up, static as well as dynamic movements could be generated over a distance of several microns. On the plate, DC creates static load and AC creates dynamic load.

The left side of Figure 2 shows result of a real-time interferometry experiment with the plate under static load. A 256×256-pixel CCD camera was used to record the image. The right side of Figure 2 shows the result of phase-shifting experiments with angles of 90˚, 180˚, and 270˚, in combination with arctan calculations. Phase signs can be recognized even by absent demodulation. The maximal deformation in the middle of the plate is 5.5µm.

Figure 3 gives an impression of the dynamic load on the bronze plate. The vibration frequency is 8.84 kilocycle/sec. The picture has been taken with a combination of real-time and phase-shifted time-averaged holography. The first picture of the loadless plate forms the initial hologram in the BR-film in real time. The dynamic load applied in real time subsequently produces vibration images even when the plate is in a resonance mode (here 8.84kHz.). A reference beam shifting with angles of 0˚, 90˚, 180˚, and 270˚ produces images I1, I2, I3 and, I4 . These images can be calculated to one image Ires given by:

f1 = (I1+I2+I3+I4)/4

Ires = SQR((I1^2+i2^2+I3^2+I4^2-4*f1^2)/2)

This calculation achieves a significant contrast enhancement, so that Ires results in very high interference contrast. This provides the ability to read out the depth of a single vibrational mode (see Figure 3). Together with stroboscopic illumination, a determination of the phase becomes possible as well.

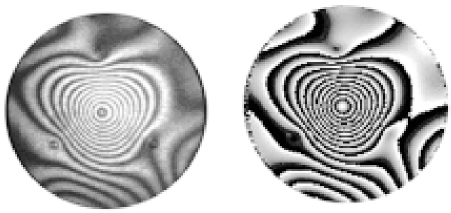

Figure 2. Shown is the static deformation of a thin bronze plate (0.15mm-thick, 100mm-diameter) in holographic real-time mode. Left: hologram without phase shifting. Right: after phase shifting with 0˚, 90˚, 180˚, 270˚. Center deformation is 3.32µm.

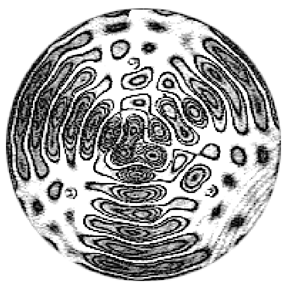

Figure 3. Bronze plate under dynamic load at 8.84Hz. A combination of real-time and time-averaged holography leads, with the addition of phase shifting, to excellent interference fringe visibility. The amplitude of adjacent vibration modes is in the range of 1.5µm.

Conclusions

BR films are novel recording materials for holographic interferometry, and have exceptional properties. These materials: (i) do not require wet chemical processing as most conventional holographic films; and (ii) are virtually unlimited in resolution (unlike typical CCD cameras).

In conjunction with a holographic camera, BR films can allow the recording of holographic images with excellent resolution, in real-time, and in a number of different recording configurations. Holographic cameras can be used for holographic measurements of a wide range of objects and are also suitable, in principle, for real-time applications in industrial environments.

The authors want to thank Dr. T. Juchem and Prof. Hampp for their discussions and experimental contributions.

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2. Holographic films based on bacteriorhodopsin and holographic recording cameras are available from MIB at the address given above.
3. T. Juchem, N. Hampp, *Holographic Camera System based on Bacteriorhodopsin,* **221 ACS National Meeting,** San Diego, CA, April 1-5, 2002.

Tell us about your news, ideas, and events!

If you're interested in sending in an article for the newsletter, have ideas for future issues, or would like to publicize an event that is coming up, we'd like to hear from you. Contact our technical editor, Sunny Bains (sunny@spie.org) to let her know what you have in mind and she'll work with you to get something ready for publication.

Deadline for the next edition, 14.1, is:

14 March 2003: Calendar items for the twelve months starting May 2003.

Deadlines for 14.2 are:

17 July 2003: Suggestions for special issues and guest editors.

25 July 2003: Ideas for articles you'd like to write (or read).

19 September 2003: Calendar items for the twelve months starting November 2003.

Holographic optical elements for window shading in buildings

Continued from page 5.

Test holograms were designed and manufactured to shade the windows of a building with a façade facing 56˚ East of South. Two holograms were recorded at 45˚ and 60˚ and were tested under a solar simulator for various solar altitudes for an entire year. The spectral transmission characteristics for different hours during the day are presented in Figures 4 and 5. The façade orientation determines that the maximum illumination takes place at 11am. It is evident from the comparison of the spectral characteristics that the shading hologram recorded at 45˚ is better suited for this application.

Hence, a hologram can be optimally designed and manufactured for the efficient shading of a building with a specified orientation. In this sense, a shading hologram exhibits some advantages over plastic shading films using multi-layered laminates. The holograms exhibit some absorption in the blue spectral range that is due to the Ammonium Dichromate and in the red that is caused by Iron ions present in standard green glass. Both holograms were red-shifted and their bandwidths increased by means of filler material diffusion and process control. The red shift and the enhanced bandwidth are of considerable advantage because they improve the control of radiant energy into the building and preserve the notion of having natural light in the room. The observer's view remains unobstructed when looking straight out of the window or downward.

Figure 5 depicts the advantages of the 2D and 3D holographic shading with respect to standard glass. The 3D shading exhibits a stronger effect, but is hampered by the fact that the transmitted light is somewhat colored and this may represent a likely drawback for this shading device. It has the advantage, however, of facilitating the achievement of larger shading bandwidths. The 2D shading shows a 20% to 30% shading efficiency for direct solar radiation. This and the color of the transmitted radiation may be improved by enlargement of the shading bandwidth and shifting it farther into the red using a more efficient infusion technique for the filler material. The goal is to enhance the shading bandwidth, so that even at maximum solar altitude angles, the red cut-off edge remains beyond visible red.

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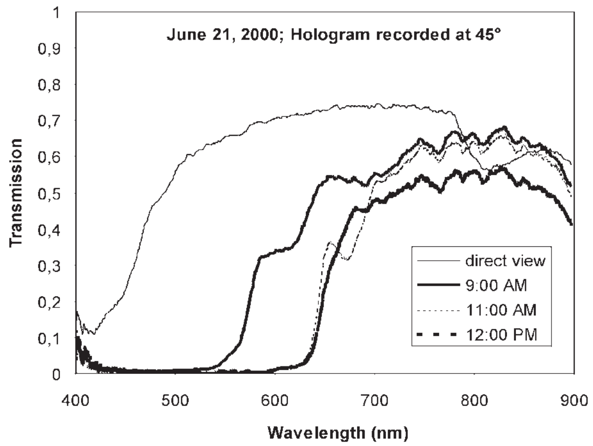

Figure 3. Spectral characteristics of 45˚ 2D-shading hologram for different hours.

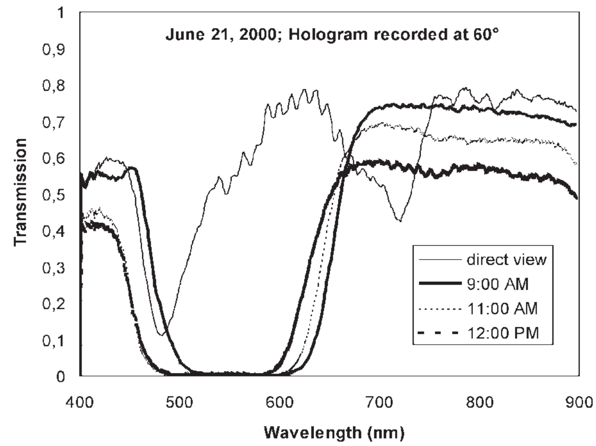

Figure 4. Spectral characteristics of 60˚ 2D-shading hologram for different hours.

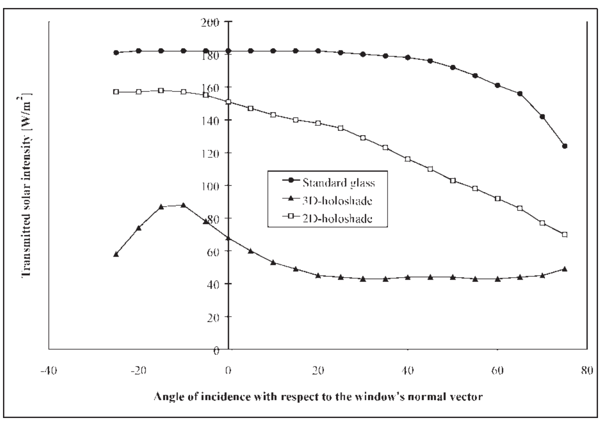

Figure 5. Efficiency comparison of 2D and 3D shading holograms.

Additive lithography for micro-optic fabrication

Continued from cover.

cific to a particular photoresist in terms of optical density and resist response. Also, gray-scale masks are highly specific to a particular design and do not provide the flexibility to allow modifications to the fabricated part without obtaining a completely new mask. Finally, gray-scale masks are highly limited in the diversity of pattern scales due to a finite number of discrete gray levels.

Additive lithography presents a fabrication alternative to either of these methods. It is compatible with conventional lithography systems used in integrated circuit manufacturing and can be applied to arbitrary thicknesses of photo-resist for micro-optic fabrication. The primary advantage of the additive method of fabrication is that each part is formed in a single processing step, eliminating the common alignment issues and substantially reducing processing time. In addition, this approach allows one to adjust the resist profile to compensate for the etch selectivity of varying substrates and to combine large features with extremely small ones in the same pattern area.

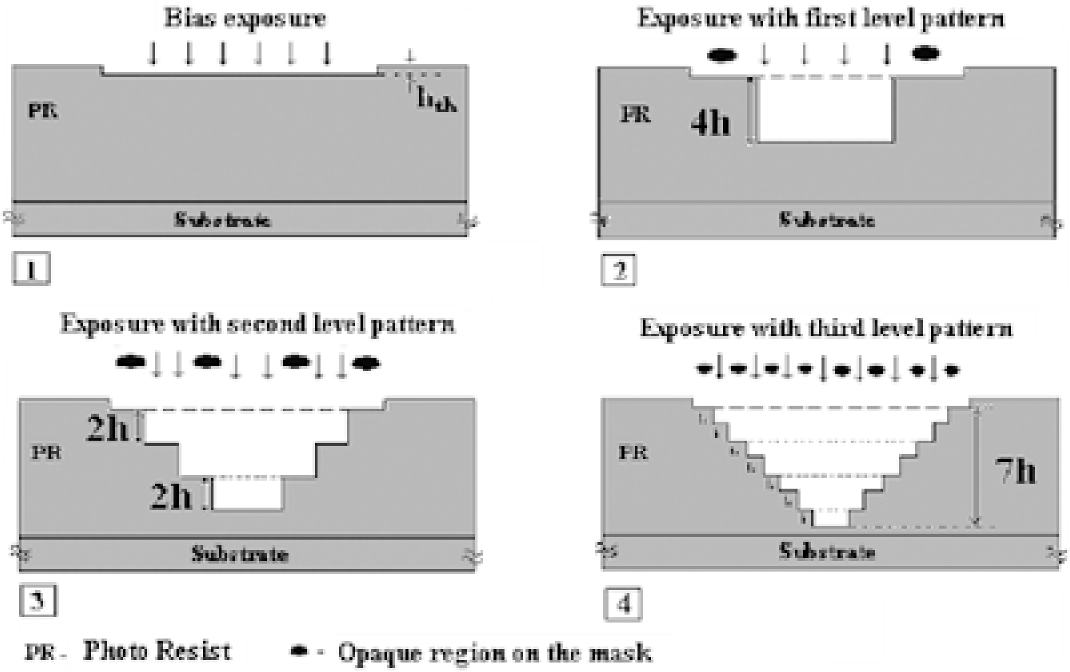

Figure 2. Additive lithography process (8-level using 2^N technique).

Additive lithography utilizes a 5× stepper system (ours is a GCA) to minimize the number of processing steps. A lithographic mask containing all the individual digital lithographic components is designed and ordered. The stepper then exposes each mask component consecutively, aligning subsequent patterns automatically based on the designed positioning of the patterns on the mask. This forms the pattern in the photoresist quickly and accurately using a single processing step. After development, the pattern can be transfer-etched into the substrate at a predetermined etch selectivity ratio corresponding to the desired optical surface sag (based on the wavelength of light used in the system for diffractive optics). Additive lithography allows for numerous combinations within its single step procedure, by means of variations in the photoresist, masking patterns, or exposure times.

This method provides a great deal of flexibility and room for experimentation. However, there is a key constraint. Multi-level optical elements, and diffractive elements (DOES) fabricated using the 2^N method in particular, require a highly linear photoresist response.

Photoresists are designed to provide high contrast. There is one key linear region, seen in Figure 1, between bias and saturation, which meets the requirements for the fabrication of multi-level DOEs using additive lithography. The linear region of the response curve, the bias dose (dose needed to reach the linear region) and the saturation dose (dose to completely clear the resist) are determined through characterization and processing of the resist.[3] It is important that the linear response region be consistent and repeatable in order to obtain consistent profile accuracy. Characterization of the photoresist verifies this, as is demonstrated in Figure 1 by the separate data taken at different times under different conditions.

The bias is overcome by pre-exposing the desired area on the wafer with the appropriate bias dose. The additive component of the process comes through a combination of varying masks. Each mask set is exposed, doubling the number of layers with each exposure. Eight levels are produced with a three-pattern mask set, as seen in Figure 2. Sixteen-level and ten-level refractive elements have also been fabricated.

We fabricated an eight-level Fresnel lens under the 2^N process, which required three masks. To do this, 1.55µm-thick photoresist was spun onto fused-silica wafers. The photoresist was then biased into the linear region, followed by three consecutive exposures of the three varying mask patterns. The lens, with 140nm-level heights, was formed on the resist corresponding to a two-phase structure at 632nm. It was then etched into the fused-silica substrate using reactive ion etching (RIE) with a 1:1.75 etch selectivity between photoresist and the substrate respectively to give level heights of approximately 235nm on the substrate. This demonstrates another benefit of the lithography and additive process: we can fabricate a multilevel structure on photoresist with level heights much higher than that required, and then, by merely adjusting the etching rate, achieve the required structure on the substrate. The Fresnel lens fabricated using the additive technique can be seen in Figure 3.

Additional advantages of the additive lithographic method involve the number of variables built into the process. The vortex element shown in Figure 4 can be fabricated for operation at different wavelengths by simply changing the overall exposure times to correspond to different step heights. Using the same mask set with different exposure times for each level, and manipulations in processing, one can form a huge range of different patterns, such as the array of positive and negative lenses demonstrated in Figure 4. Also, patterns of vastly different size and characteristics can easily be combined together as we demonstrate in Figure 5, with the combination of a holographic grating multiplexed on an 8-level diffractive lens. A grating has also been combined with a

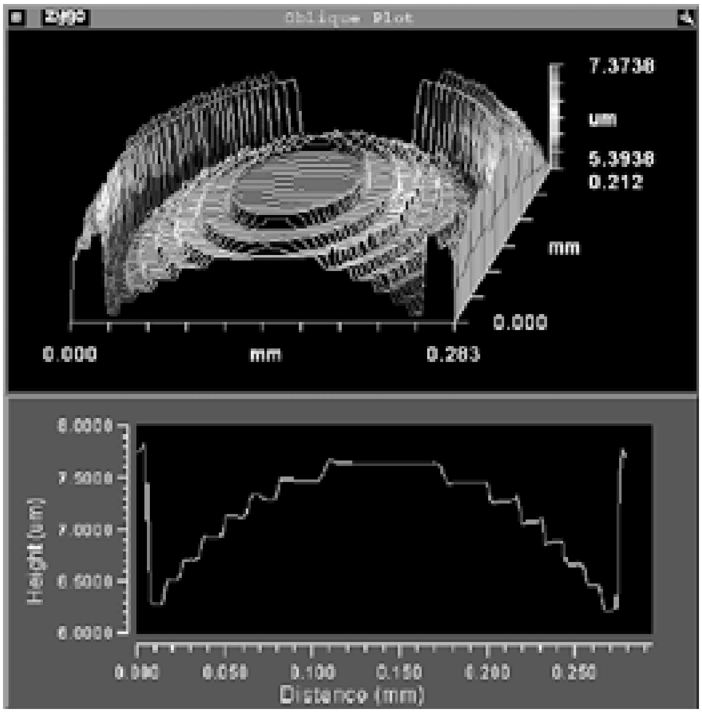

Figure 3. 8 level fresnel lens on fused silica 3D and 2D profile.

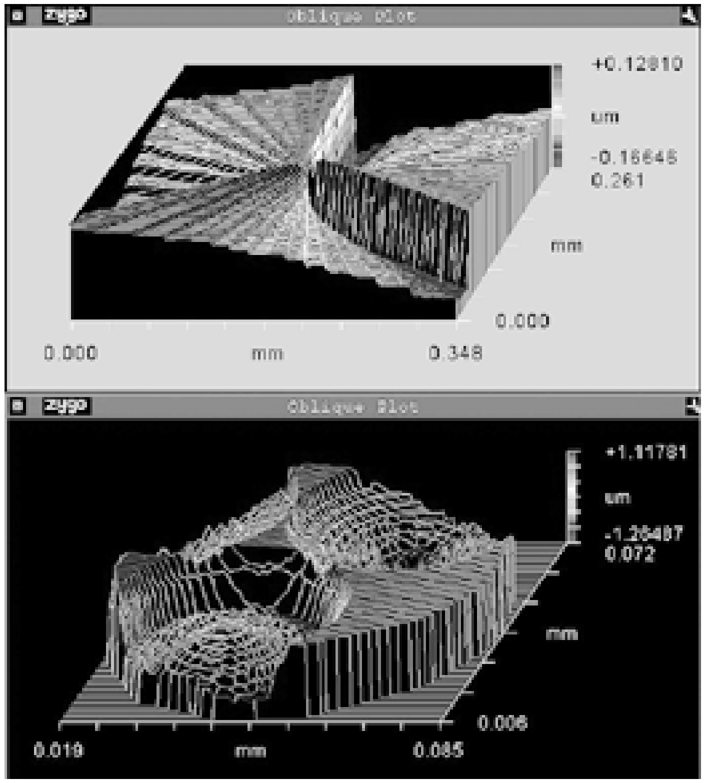

Figure 4. Top: Shown is a 16-level vortex lens (Charge = 3). Bottom: Positive and negative lenses in a hex array.

gray-scale lens. Any arbitrary set of patterns may be combined, from deep-sag gray-scale refractive lenses, to small amplitude binary gratings. As we continue to explore the potentials of the additive technique, more innovations continue to lend themselves to this approach.

Additive lithography is both a creative and flexible approach for fabricating complex diffractive and refractive optical elements on the wafer scale. This approach greatly decreases the potential for alignment error while increasing the applications for fabrication using each masking set. It is yet to be determined how many possible variations of optical elements can be fabricated using this novel yet reproducible approach. However, the true advantages lie in the low cost of production, high tolerance, and flexibility demonstrated by the additive method of lithography.

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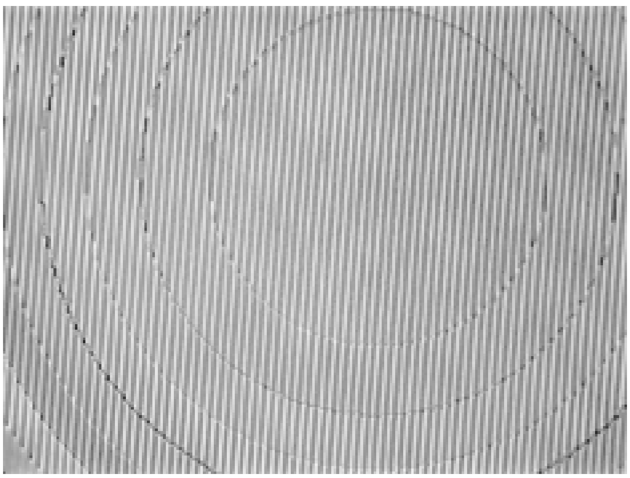

Figure 5. Holographic grating multiplexed on a 8-level diffractive lens.

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An update on commercial recording materials

Continued from page 2.

of holographic photopolymer materials is *E.I. du Pont de Nemours & Co.*. In the past it was possible to obtain photopolymer materials from DuPont, but in 2002 the company changed its policy and today it is producing materials mainly for DuPont Holographics. Approved customers may still be able to buy material from DuPont. The reason for the restriction is that many applications of mass-produced holograms are in the field of document security, where DuPont's photopolymers are used to produce optical variable devices (OVDs).

Commercial photoresist materials

The main American manufacturer of photoresist is *Shipley Co.*. There are a few companies which make photoresist recording plates for holography based on the Shipley material.

- *Towne Technologies, Inc.* produces spin-coated plates using Shipley resist (Shipley S-1800 series). Towne plates have a sub-layer of iron oxide that enhances adhesion of the resist during electro-plating operations. In addition, the sub-layer eliminates unwanted back scatter from the glass substrate. The plates are developed in Shipley 303A developer.
- *Hoya Corporation* is a producer of mask blanks coated with 0.5µm-thick Shipley S-1800 resist (SLW plates). Different types of glass and quartz plates are produced. Hoya supply plates for holography, but only custom orders.

Commercial thermoplastic materials

Several companies produced thermoplastic materials and recording equipment for holography in the past. However, since there is very little demand for such materials today, there is only one company which can deliver thermoplastic equipment for holography.

- *Tavex America Inc.* manufactures a thermoplastic camera, TCC-2 in which 40×40mm plates are used. For obsolete systems, thermoplastic film can still be obtained from *MD Diffusion* in France.

Commercial Bacteriorhodopsin (BR) materials

- A holographic camera based on a BR film is manufactured in Germany. The holographic system, FringeMaker-*plus*, developed at the University of Marburg is marketed by *Munich Innovation Biomaterials (MIB) GmbH*. Holograms are recorded on erasable BR film and the resulting interferograms are recorded via a CCD camera.

MIB is also a manufacturer of both wild-type and genetically-modified BR film for holography and other scientific/technical applications. BR-films offered by MIB can be used in two different recording configurations: the transition from the initial B to M-state (induced with yellow light) serves as a basis for optical data recording and processing (B-type recording); or the photochemically-induced transition from M to B state (M-type recording). In the latter case, yellow light is used to control the population of the M-state and blue light is used to write the information. MIB offers BR-films with normal and slow thermal-relaxation characteristics. Typical relaxation time ranges (RTR) after which the photochemically-excited BR molecules have returned to the original state, are between 0.3s and 80s. The BR film is sealed between two windows of high-quality optical glass. The BR film layer has a thickness of 30–100µm, dependent on the optical density of the film. The diameter of the film device is 25mm and the clear aperture is 19mm.

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Ripple Tank collective to produce holographic book

The artist collective known as the *Ripple Tank* has begun production of the first limited-edition book of digital holographic works by artists. The book, entitled *LikeAge*, is viewed as a fine art publication, and only 21 copies will be produced and distributed.

The *Ripple Tank* uses the Photon League Studios to produce their work. The Photon League is an artists-run centre for holography established in 1985 in Toronto.[1] The work is also sponsored in part by the Ontario College of Art & Design. Nancy Paterson, the project curator, is internationally known for her multimedia work and writing.[2]

Ten artists have produced digital artwork for printing using the Light Valve holographic printer. The printer, developed by Photonix Imaging in Toronto, uses an SLM (spatial light modulator) or light valve to produce high-resolution holograms for 3D computer artwork.[3]

In contrast to most holographic artworks, which are precious objects that are preserved in frames, the holographic book represents a more perishable and yet intimate form for the visitor to the gallery. Each of the ten artists represented in the book will receive a copy of the book at the end of the exhibition, along with a custom-made podium. Contributors to the book will then possess a record or document of work by their peers.

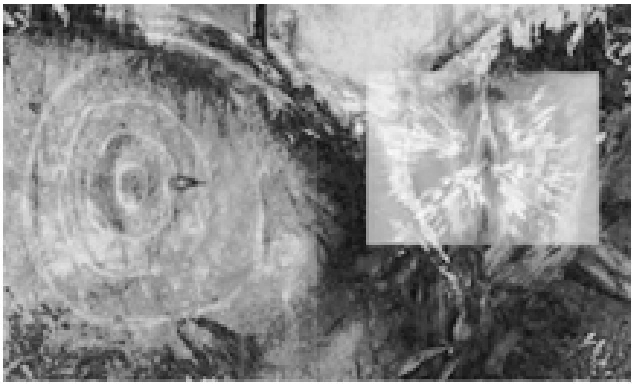

Figure 1. Work by Wendy Whaley from the forthcoming Ripple Tank holographic book.

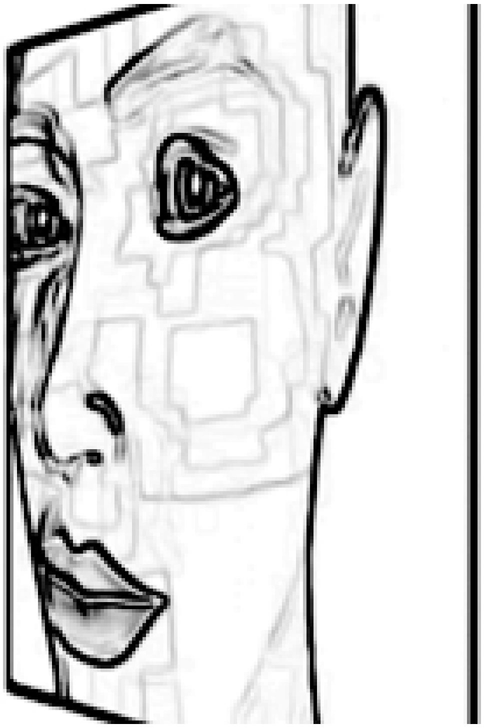

Figure 2. Holographic artwork by Ripple Tank artist David Harris-Smith to be published in forthcoming book.

The book will be hand-sewn and bound. Each hologram is handmade. Epson Canada has donated archival inks and papers to the project that are predicted to last up to 300 years. It will be one of the most expensive new books ever sold at $6,000 per copy.

Three copies of the book will be awarded to corporate sponsors of the project. The remaining eight in the edition will be offered up for sale to cover the cost of producing the books and the cost of travelling the exhibition, which has tentative dates in Toronto and the U.S.

The National Library of Canada requires, by law, that a free copy of all books published on Canadian soil be given to the Government. The group has announced its intention not to provide a book to the Library, citing the high cost of production and questioning the position taken by the National Library, which doesn't fairly compensate makers of art books for their efforts. A spokesperson for the National Library stated that the government would have no choice but to prosecute those who would not comply with the law. The group intends to bring about change in the legislation through its act of civil disobedience.

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