Advances in digital holography

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Digital holography development has reached the level, which allows mass-manufacture of large size digital holograms – i-Lumograms, as well as manufacture of colour reflection holograms for security applications. Geola Digital also has proved that colour reflection holograms can be used as auto-stereoscopic projection displays for 3D gaming and home cinema applications. All that became possible by developing a full range of necessary holographic machinery that includes digital laserless life scenes imaging equipment, digital holographic printers and copying machines where our new copying method is implemented. Printing and copying machinery works with pulsed colour lasers. All Geola machinery exists as working laboratory equipment and is used by us for continuous printing of digital holograms. Image creation, hologram printing and copying processes can be completely separated geographically.

Key words: Digital Holography, Contact Copy, Holographic Imaging, Autostereoscopic, 3D projection, 3D television, Holographic, Projection screen

1. Introduction

Digital holographic printing is a photomaterial exposing technique where object beam is formed by spatially modulating one of the laser radiation beams and another beam is used as reference beam. The modulation is performed in such a way that resulting object beam at the place of its interference with reference beam contains same information that would come to this point from a real object if this object would be used for holographic recording. In digital holography instead of the real object, series of its digital photographs taken from different angles are used. That allows obtaining enough information for single and full parallax digital holograms.

Object beam modulation pattern is calculated from ensembles of corresponding digital photographs pixels characteristics (Fig.1). Object beam is modulated by displaying this calculated pattern on transparent (or how it was implemented recently, on reflective) LCD display and illuminating this display by laser beam.

In digital holography it is enough to have digital pictures of object to be imprinted, so imaging and printing processes can be, and usually are, geographically separated. Until recently, images for digital holographic printing were obtained by rendering digitally created scenes using 3D modeling programs rendering engines. We have developed a device enabling to obtain needed images from live scenes.

Since information for digital hologram is obtained from digital pictures pixels, the hologram itself always has pixilated structure. Those holographic pixels are called holopixels (Geola) or hogels (Zebra Imaging), currently the size of those holopixels is not less than 0.8 x 0.8 mm, and each holopixel contains information from 600-1200 usual pixels with corresponding coordinates that are taken from different views of imprinted scene.

Spatially modulated object beams together with reference laser radiation beam are exposing one holopixel on unexposed photomaterial. Then holographic media shall be moved for the distance equal to holopixel size and next holopixel is exposed. For colour digital holograms each holopixel shall be exposed three times with Red, Green and Blue lasers. Highest quality digital hologram shall contain

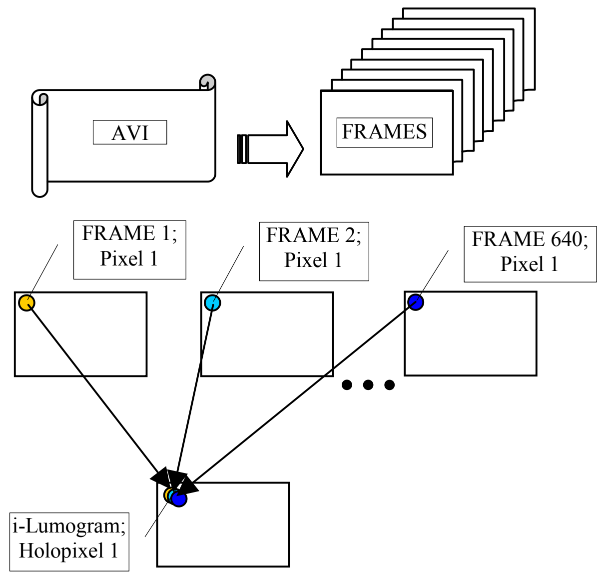

Fig. 1. Holopixel formation

holopixels, which size would be at least equal to digital displays pixels pitch (0.24mm) and noticeably bigger quantities of such holograms shall be printed during a reasonable time period. If we want to reduce holopixel size keeping the same printing speed or increasing it, we need to have more speedy (or in CW lasers case, more powerful) lasers and speedier and more efficient LCDs used for spatial modulation. But then mechanical system stability will prevent further printing speed increase, however till certain mechanical system speed pulsed lasers seem to be a perfect solution for limitations caused by system vibration.

Obvious solution then seems to print one digital hologram with pulsed RGB laser, as fast as possible, and use copying to multiply it. However obvious, this solution required us to develop pulsed RGB laser, Silver Halide photomaterial sensitive to pulse laser radiation, digital holographic printer and copier. To make digital holography tools available for common people and to move holographic imaging outside laboratories, we have also developed life imaging devices and lighting solution. So from now on it becomes possible to use digital holography for commercial full colour reflection holograms manufacturing.

Such digital reflection holograms can be full colour security or advertising holograms as well as reflection holographic autostereoscopic screens. Our hologram copying method might be used as well for producing Denysiuk type holograms of paintings and holographic memories copying.

Herebelow will be discussed all digital holography tools developed by Geola alone or with cooperation with other researchers. Also there will be discussed digital reflection holograms use as autostereoscopic reflection screens.

2. Silver halide photoemulsion used in digital holography

In parallel with pulsed RGB lasers and holographic printers development, we needed a new photomaterial to be developed. All existing photomaterials ether had too big grain size (which led to unacceptable light scattering in the blue wavelengths region) or were not sensitive enough for pulsed laser radiation. New Silver Halide photoemulsion which characteristics are given below was developed together with other researchers [1)]. This photoemulsion has Silver grain size of 10 nanometers and is more sensitive to pulsed lasers radiation, than to CW lasers radiation. Photomaterial in the form of photofilm of 1.1 meter width is commercially available in large quantities.

2.1 Spectral sensitization

Since the photoemulsion was especially designed for use in conjunction with Geola's pulsed lasers, the sensitizing dyes were chosen to be close to the said pulsed lasers emitting wavelengths and photoemulsion was coated onto transparent triacetate base. Thus the maximums of the new photofilm spectral sensitization are at 450nm, 530nm and 660nm. However, as shown below, this does not limit the usage of the film to the use with Geola's pulsed lasers only - the film is perfectly suitable for usage with the more common CW lasers.

2.2 Grain size and other physical parameters

The grain size of our film was evaluated by its comparison with known emulsions from Slavich made for Geola. We have compared the blue pulsed laser light scattering by the known VRP-M, PFG-01, PFG-03M and PFG-03C emulsions coated on the same triacetate substrate as the new film, with the new film. The blue light scattering obtained from the new film was a bit lower than the one from PFG-03C film which is known as having a grain size of ~10nm. Thus we can conclude that the new film has the grain size also of ~10nm. The other photographic characteristics of the film are given in the table 1. The film shows a high contrast level and a good characteristic curve density. This indicates that new film is also suitable for laser lithography and for the precise photomasks recording.

Table 1. Physical parameters of the new film

Maximum density on characteristic curve (Dmax)	4.0
Fog level (D0)	0.1
Emulsion layer thickness (microns)	7 to 8
Contrast	7
Observed life period at 20o Celsius, 45% humidity.	
Unwounded film roll (months)	36
Rewounded film roll (months)	3
Cut sheets (months)	3

2.3 Absorption spectrum

Figure 1 shows our photoemulsion absorption spectrum. The light absorption of the film is relatively small – the film, while observing it by eye, looks clear, but at the wavelengths of the commonly used lasers it shows bigger absorption. That indicates that the film is sensitive to the entire visible light spectrum. Indeed, the holographic recording of diffuse mirrors followed by the measurement of their diffraction efficiency, as discussed below, shows the film's ability to record various colour holograms with high diffraction efficiency.

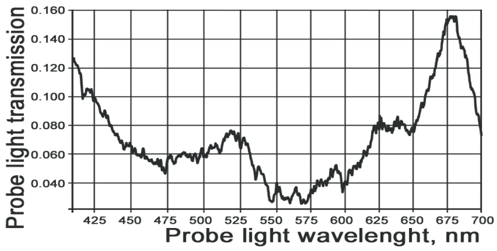

Fig 2. New photomaterial absorption spectrum.

2.4 Diffraction efficiency

The diffraction efficiency of the new film was investigated by recording diffuse holographic mirrors using the usual two opposite beams scheme with diffusion of one of the beams followed by its collimation. As a light source we used usual CW lasers with a good coherence length (HeNe and Ar) and Geola's pulsed RGB lasers (coherence length >3meters). We used emulsion from six different batches. The chemical developing of the materials was done with the usual SM-6 developer and PBU-Amidol bleach, followed by drying of the emulsion layer in an alcohol-water solution. Since the emulsion is softer than those with bigger grain size, we needed to harden it before developing. The temperature of all solutions was 21 degrees Celsius.

When processed and dried, the film sometimes shows a replay wavelength shift of ~25nm mirrors towards the blue region of visible light spectrum from the wavelengths used for the recording: i.e., for example when a pulsed laser with the wavelength of 660nm is used, the hologram replay maximum is at 630-640nm. This shift can be controlled by slightly changing the chemistry and solutions temperatures.

Table 2 summarizes the results of an investigation of the new film's diffraction efficiency. In the table are put exposures that correspond to the highest observed diffraction efficiencies. As it is seen, the diffraction efficiency of the holograms recorded with convenient CW lasers is about twice as large as those recorded with the pulsed lasers. And at the same time, in order to achieve the maximum diffraction efficiency with CW lasers, from 3.5 to

10 times larger exposures are needed. These facts cannot be explained with classic photophysics theories. Since the grain size of the new materials is ~10nm, we assume that the energy levels of the silver ion grains and dyes should be taken into account, together with the different conductors's life times at the particular energy levels. This needs separate investigation.

Table 2: Sensitivity and diffraction efficiency

Parameters	Measured values
Exposure,	microJ/cm2
@ 457nm, CW	1250±200
@ 440nm, ~30ns pulse	120±20
@ 514.5nm, CW	1800±200
@ 532nm, ~30ns pulse	330±30
@ 633nm, CW	1900±250
@ 660nm, ~30ns pulse	550±50
Diffraction efficiency for reflection holograms (diffused mirrors),	%
@ 457nm, CW	27.0±3
@ 440nm, ~30ns pulse	14.0±2
@ 514.5nm, CW	35.8±3
@ 532nm, ~30ns pulse	16.5±2
@ 660nm, ~30ns pulse	14.2±2
@ 633nm, CW	38.3±3

2. Holographic printing, copying and imaging

2.1 Classical HoloPrinter

The detailed design of our currently operated 1-step and master holographic printers is described in two PCT patent applications [2,3]. Fig.1 depicts a simplified schematic diagram of a printer. Red, Green and Blue pulsed lasers are employed which typically each produce several millijoules of energy at respectively 660nm, 532nm and 440nm at a pulse duration of 35-50ns depending on design. The laser outputs are highly coherent single longitudinal mode emissions and spatial structure is TEM00. The three laser beams are each split into an object beam and a reference beam by a set of motorized half-waveplates paired with polarizing beamsplitters that are controlled by the system computer. The energy of each laser emission is likewise controlled internally by the same method. This allows the system computer to control and set automatically the beam energies and the beam ratios.

Digital image data is encoded onto the object beams via transmissive LCD displays such as XGA1 panels from Sony. Prior to illumination of the LCD panels the object beam is conditioned by a system based on a 2D micro-lens array. By controlling an aperture directly in front of the micro-lens array differently shaped and sized holopixels may be created with ease. A correct choice of the characteristics of the micro-lens array and the associated optics is essential if a spatially uniform holopixel capable of replaying digital image data at high angular resolution is to be achieved.

Three special high numerical aperture telecentric objectives, each having a diagonal field of view of typically 100 degrees, are used to focus down the three digitally encoded object beams to minimum beam waists, which occur at or very near to the photosensitive film surface and whose footprints define the respective holopixel. The design of these objectives is such that a high quality image of each LCD is created at a distance downstream from the photosensitive film, which corresponds usually to the hologram viewing distance (the image plane of the LCD can be situated from the viewing plane to infinity).

Each quasi-collimated reference beam is traditionally conditioned by a telescopic system that forms a soft image of an elliptical aperture at the photosensitive film surface. The elliptical aperture compensates for the 45-degree inclination of the reference beam to the film surface, thereby forming a soft circular footprint coincident to, and slightly larger than, the corresponding, normally square, object beam footprint.

The hologram is written when the photosensitive film or photosensitive glass plate is made to move horizontally at constant velocity as the lasers fire regularly. In this way a single line of juxtaposing holopixels are created. The film or plate is now made to move up vertically by the diameter of one holopixel and then the same process writes a second line in the inverse direction. This process continues until the hologram has been completely written row by row.

The energy stability is vitally important for smooth operation, as the long-cavity pulsed lasers used in these printer designs fire the lasers at the same repetition rate. The velocity of the film movement must be constant, and it is also necessary to synchronize the LCD write cycle properly.

2.2 Improved HoloPrinter

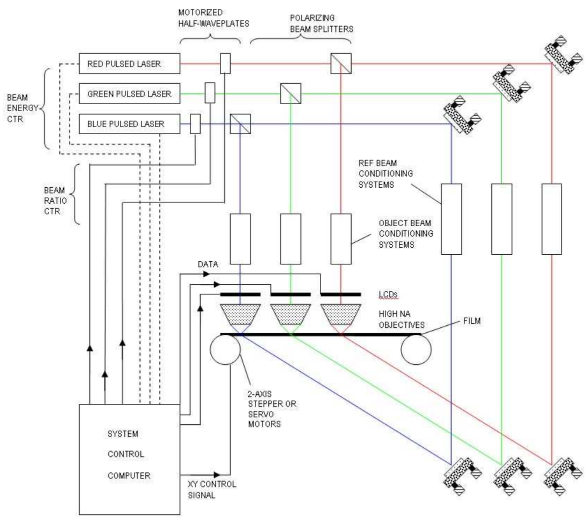

Fig.4 Simplified Schematic Diagram of a Current 1-step or Master Holographic Printer

Holographic printer described above is quite robust and is used in our facilities for continuous digital hologram printing. However for increasing digital holograms demand, the speed of our current printer is rather low. Therefore we have investigated possibilities to increase holographic photomaterials exposure frequency. For that purpose we have developed a short-cavity pulsed RGB laser working with up to 200Hz flashing frequency and used LCOS (liquid crystal on silicon) displays for object beam modulation. To prove the concept, working models of all new printer elements were assembled and tested [4)]. Digital reflection holograms with holopixel sizes ranging from 0.25mm to 1mm were printed using only new printer elements. The new concept printer elements are discussed in details below.

The schematic diagram of the fast new concept printer is shown on Fig.5. As classical Geola HoloPrinter, the new concept printer is suitable for writing master or 1-step holograms holopixel by holopixel. The printer is based on 3 LCOS panels and red (660nm), green (532nm) and blue (440nm) short-cavity pulsed lasers. For clarity Fig.10 only shows the printer schematic for a single colour laser emission. Physically the beam-paths for each three colours are stacked identically one on top of the other.

A small cavity TEM00 SLM laser (101) emits a pulsed laser beam (3mm diameter, 0.4mJ for 660nm), which traverses the motorized ½ waveplate 102. The laser beam then continues on to the Brewster-angle polarizer 104 where it is split into a reference and object beam. Further downstream two energy meters (147,145) measure the energies in these two beams. By activating the stepper motor 103 the system control computer can accurately control the reference beam energy.

2.2.1 Object Beam Arm

The object beam originates at the polarizer 104 and immediately traverses the ½ waveplate 120, which is controlled by the stepping motor 121. It then traverses the Brewster angle polarizer (down-facing) 148 where excess energy in the wrong polarization is dumped. The mirror 122 now guides the object beam onto a series of two mirrors (149,128), which are mounted on a precision translation stage 124. This stage is mounted on precision rails (126,127) and is controlled by the stepping motor 125. The system control computer can control the beam path length of the object beam by controlling this motor. As the rail moves back and forth the beam directions remain invariant but the beam path length changes. This allows the object and reference beam paths to be exactly matched.

Before traversing a coated wedge 144 the object beam is then reflected by the mirrors 128 and 129. This wedge is cut at 10 degrees and its rear-surface is anti-reflection coated (660nm for red object beam, 440nm for blue object beam and 532nm for green object beam). The wedge allows most of the object beam to traverse it unchanged whilst reflecting a few percent to the GEM-SI-7511 energy meter 145. This energy meter is calibrated to read the object beam energy and is connected via USB cable to the system control computer. The object beam now continues to the aperture 130 and to a microlens array (131). The shape and size of the aperture determines the shape and size of the final holographic pixel (116). Usually a square shape is used. An aperture dimension of 9mm x 9mm corresponds to a holographic pixel size of 1mm x 1mm at the photosensitive film 117. We have used various microlens arrays depending on the LCOS display panel used. For the BR768HC display panel (available from HOLOEYE and made by Brillian) we use a lens array of 50mm in diameter, made from BK7 (or K8) and containing rectangularly packed 0.2mmx0.23mm lenslets each with a radius of curvature of 0.65mm. On illumination by the squarely formed object beam the lens array produces a beam of rectangular beam profile downstream. This profile is chosen (through the design of the lens array) to fit the LCOS display 137. The object beam

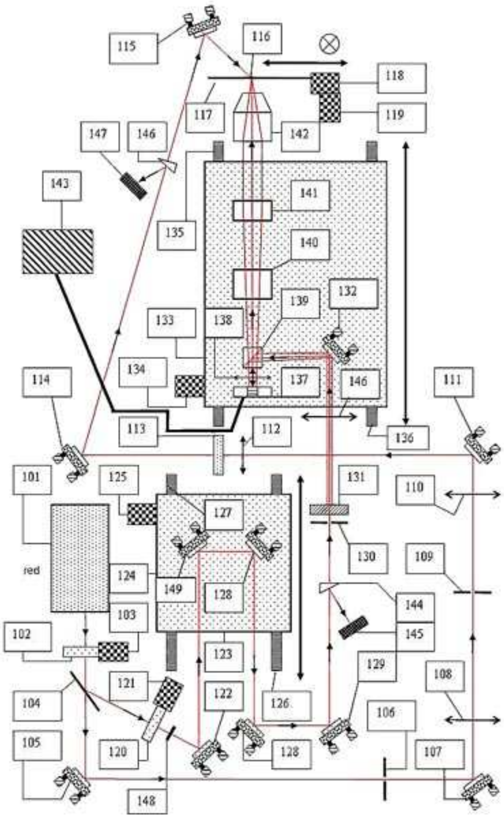

Fig.5. Holographic Printer based on LCOS and short-cavity laser technology.

downstream of the lens array is conditioned by the lens 146 and then reflected by the mirror 132 onto a McNeale type polarizing beamsplitter (139) whereupon the light is reflected and passes through a field curvature correction lens (138) to illuminate the small LCOS panel (137). We have used several panels but prefer the BR768HC panel which measures 17.91mm diagonal, has a 12-micron pixel pitch, a fill factor of 92%, a reflectivity of 71% and a frame rate of 120Hz.

The object beam that is reflected from the LCOS panel is modulated by a digital image, which is supplied by the system control computer and is derived from pixel-swapped image data. LCOS panel performs object beam phase modulation. Digital data are encoded in this modulation. When the object beam passes back through the McNeale polarizer (139) this phase modulation is converted to an amplitude modulation. This amplitude modulated object beam then passes through a special telecentric afocal reversing system (140, 141) before being "focused" to the holographic pixel (116) by the high numerical-aperture telecentric objective lens system having an FOV of greater than 100 degrees (142).

The LCOS panel (137), the field curvature correction lens (138), the telecentric afocal reversing system (140, 141), the McNeale polarizing cube (139) and the mirror 132 are all mounted on a precision translation stage (133) with rails 135 and 136, controlled by a stepper motor 134. The system control computer can use the motor 134 to adjust the distance at which a focused real image of the LCOS panel appears in space behind the photosensitive medium. This is usually chosen to correspond to the viewing distance of the hologram being printed.

A Proflux thin-wire polarizing beamsplitter can also be used instead of the McNeale type. We prefer the McNeale polarizers as they damage less easily.

2.2.2 Reference Beam Arm

The reference beam originates at the polarizer 104 and is reflected by the mirror 105 to the aperture 106. This aperture is elliptical. An image of this aperture is formed by the lens system comprising the lenses 108, 110 and 112 at the photosensitive film surface 116. Since the reference beam intersects the photosensitive film at an angle (usually close to 45 degrees) the final reference beam footprint is circular rather than elliptical.

The reference beam passing through the aperture 106 reflects off the mirror 108 and then passes through a small pinhole 109 (typically 0.2-0.8mm). This pinhole acts as a spatial filter and cleans up the beam. Note that the energy is so low that no electro-optical breakdown occurs. Since the pinhole removes high spatial frequencies it also softens the image of the aperture 106 at the film surface 116. In this way a nicely Gaussian circular reference beam is created at the holographic pixel location.

The reference beam continues to propagate from the pinhole (109) through the lens, 110. It is then reflected off the mirror 111 and traverses the lens 112. A polarizer 113 removes any unwanted polarization. The beam is then reflected off the mirror 114. A wedge 146 now reflects a few percent of the object beam back to a GEM-SI-7511 energy meter 147. This allows the system computer to monitor the reference beam energy. Note that the backside of the wedge is AR coated. The reference beam now continues on to the mirror 115 where it is reflected to intersect the photosensitive material 117 at the holographic pixel 116. The (usually) circular reference beam (301) is made to be a little larger than the (usually) square footprint (302) of the object beam at the photosensitive material surface. The centre axial rays of both the object and reference beams intersect at the surface of the photosensitive material.

2.2.3 Results

Using concept printer modules, we were able to print reflection holograms with holopixel sizes ranging from 0.25mm to 1mm at a speed of up to 50Hz on photoemulsion described above. The limitation in speed is purely due to components used in the new concept printer elements modelling. We have more than enough energy from our short-cavity lasers. It is clear that we can increase the print-speed to the LCOS panel limit of 120Hz. With the latest VAN LCOS panels commercially available from Sony, print speeds approaching 200Hz should be possible.

2.3 Geola holographic copier

Hologram contact copying using slit-shaped laser beam is known from 1973 [5)]. In all implemented variations of this method a slit-shaped laser beam was forced to move through a non-exposed photomaterial laying on master hologram as shown on Fig. 6.

The coherent laser radiation reconstructs the information recorded on the master hologram, i.e. becomes the object beam and the reference beam simultaneously exposing the previously non-exposed light sensitive material. As a result of the interference of these two beams, the data stored in the master hologram is recorded on the previously non-exposed light sensitive material. The zone of the master hologram illuminated by the slit shaped laser beam is perpendicular to the projection of the coherent light directed toward the surface of the master hologram. The slit zone is transported on the surface of the non-exposed light sensitive material in the direction that is parallel to the said projection of the coherent light falling direction onto the master hologram surface.

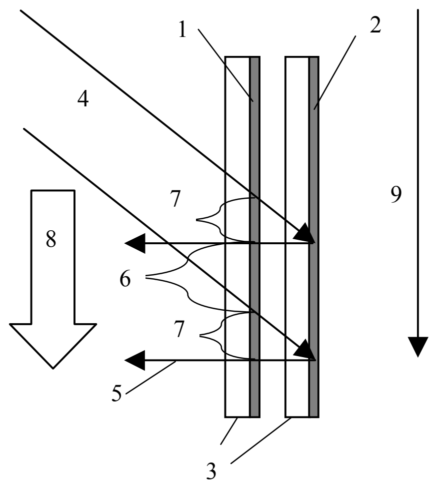

Fig. 6. Classical contact copying scheme using slit-shaped laser beam, side view. 1 – non-exposed photomaterial; 2 – master hologram; 3 – bases; 4 – slit-shaped laser beam; 5 – master hologram replay direction; 6 – place on non-exposed photomaterial where object and reference beams interfere; 7 – parasitic exposure areas; 8 – slit-shaped laser beam movement; 9 – laser beam direction projection to media surface

The drawback of this method in contact copying is that part of the non-exposed light sensitive material, illuminated by the object and reference light beams, always remains unexposed by both beams simultaneously. This occurs because the zone illuminated by the narrow slit-shaped laser beam, is perpendicular to the projection of the coherent light falling direction onto the master hologram surface. Therefore, the parasitic noise, which reduces the copy quality, was always recorded together with the effective image information. This zone of the parasitic exposure increases as the distance between the master hologram and the non-exposed light sensitive material diverges and as an angle of incidence of coherent light beam during the contact copying becomes more acute. Since the master hologram per se is usually recorded on the light sensitive material and is placed on the same base, the gap between the master hologram and non-exposed light sensitive material always exists, and the angle of coherent light beam incidence might reach 15-20°.

This parasitic exposure may be reduced by placing master hologram on a drum and focusing slit-shaped laser beam into a certain place inside this drum. Any known method would not allow to completely avoid this parasitic exposure, caused by copying geometry itself.

Geola's contact copying method is based on a different contact copying geometry, which minimizes parasitic exposure to the level where it becomes suitable for industrial hologram copying applications. The key point of this method is that the zone illuminated by a slit-shaped laser beam is parallel to the laser beam falling direction projection to the non-exposed photomaterial and master hologram (Fig. 7.).

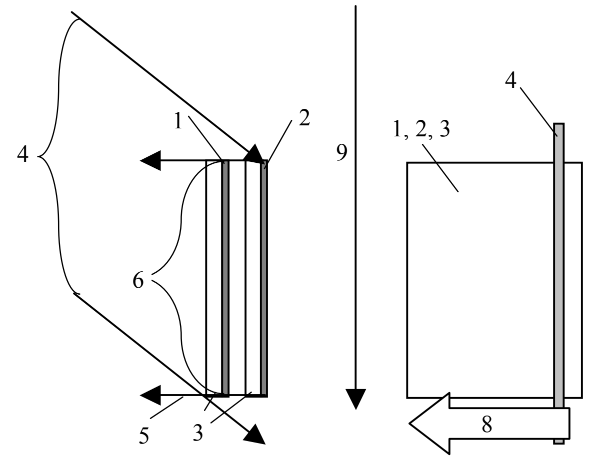

Fig. 7. Geola' contact copying scheme using slit-shaped laser beam. Side (left) and front (right) views. 1 – non-exposed photomaterial; 2 – master hologram; 3 – bases; 4 – slit-shaped laser beam; 5 – master hologram replay direction; 6 – place on non-exposed photomaterial where object and reference beams interfere; 8 – slit-shaped laser beam movement; 9 – laser beam direction projection to media surface

As it is seen from Fig. 7. – no parasitic exposure is present in the maximum master hologram replay direction. However, since the master hologram usually replays not only in the direction perpendicular to hologram surface, some parasitic exposure, caused by not perpendicular master replays still exist even in this geometry. Fortunately, the intensity of this side exposure is a lot smaller than our Silver Halide emulsion optimum sensitivity level and it does not affect the quality of hologram copies.

Our contact copying method [6)] was implemented into HoloCopier prototype, which now is used in our laboratory for contact copying of digital holograms. The schematics of HoloCopier are shown on Fig. 8.

As a coherent light source we have used our standard RGB pulsed laser [7)] that emits 440, 532 and 660 nanometers wavelengths and gives 3-4 millijoules energy in each of the three colour pulses with duration of 40ns. Master hologram maximum replay wavelengths shall match the exposing laser wavelengths – a special master hologram development process that prevents Silver Halide emulsion shrinkage during its chemical processing achieves this.

Each of the laser 11 radiation beams passes computer-controlled wave plates 12 and polarizers 13. By rotating waveplates 12 we are adjusting desired colour balance of hologram copy. After that beams are cleaned with spatial filters 14. The polarization correctors 15 compensate spatial filters 14 polarization. Then the beams by the mirrors 16 are directed to the three-colour combiner-deflector 17. The beams from the combiner-deflector 17 are heading in the same direction and way, directed to the laser radiation beam

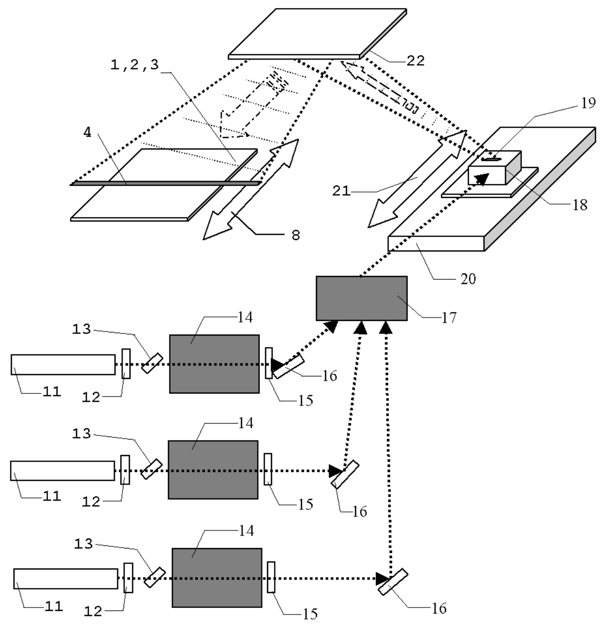

Fig.8. Geola's hologram copier working prototype.

shaping/deflection system 18. This system forms laser radiation beam into shape of the narrow elongated oval slit. Then beam, reflected by flat mirror 22, falls onto the non-exposed light sensitive material 1 and onto the master hologram or holographic print 2.

The zone illuminated by laser radiation beam 4 is parallel to this beam projection to master hologram and non-exposed material surfaces. The laser radiation shaping/deflection system 18 is fixed on the computer controlled translation motion mover 20, which assures its even movement in direction 21. At the same time the translation motion mover 20 assures the coherent light radiation movement in direction 8, which is perpendicular to the projection of the coherent lighting beam, that illuminates the master hologram, falling direction to the master hologram plane. This assures the even exposure of non-exposed light sensitive material and master hologram, causing the even recording of the reconstructed master hologram data.

Unfortunately, existing Silver Halide photoemulsions do not allow producing full colour contact copies with diffraction efficiency greater that diffraction efficiency of master hologram. Best result that we were able to achieve was colour copies with diffraction efficiency of (in percentage from master diffraction efficiency) 100% in Red and Green colour and 50% in Blue. That should be improved by using different Silver Halide photoemulsion, which, we hope, will be developed in the nearest future. However if copy is made only with two colour laser radiations, its diffraction efficiency can reach 150% of the master hologram efficiency.

2.3.1 Results

Using this copier prototype we were able to record colour Denysiuk type holograms of relief surfaces, thus it is suitable not only for holographic storage information copying but also for oil paintings and other artifacts memorizing by holographic means.

We believe that such hologram contact copying method also can be used in holographic ROM memories mass production, however this topic needs further investigation.

2.4 HoloCam

Modern digital holographic printers placed new requirements on image capture systems for the production of real-life objects holograms. Because of the hologram size (up to 1x1.5m), at least 600 pictures required to be captured within a few seconds from a real-life scene for horizontal parallax only (HPO) holograms. Additionally the field of view of such holograms has risen up to 90 degrees. Typical modern printers therefore require image data to be collected from a camera that has an field of view (FOV) of approximately 90 degrees - Fig 9.

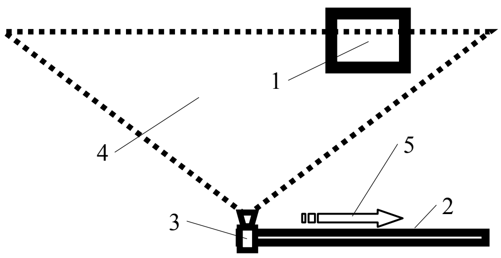

Fig. 9 A diagram of a perfectly translating high-FOV camera on a rail. 1. A scene to be filmed with a high-FOV camera on a rail; 2. Linear translation rail; 3. High-FOV camera at the left-most position at the linear translation rail; 4. FOV of the high-FOV camera; 5. High-FOV camera movement.

Fortunately, digital printer requires rather small resolution of digital frames – since information needed for one holopixel is obtained from ensemble of usual pixels with ratio 1:1, the resulting quantity of pixels needed in digital frames is defined by holopixel size. E.g. if holopixel size is 0.8 x 0.8 mm and the desired size of a digital hologram is 600x400mm, resolution of digital frames used for digital holographic printing is 750x500 pixels. It would seem that resolution of final digital hologram will be rather small, but since each holopixel contains information from up to 1000 conventional pixels, amount of visual information stored on digital hologram corresponds to information amount perceptible from usual flat print with two to four times bigger pixels density.

However small digital frames resolution is needed for digital holographic printing, conventional solutions for image capture of a real world scene of translating a forward facing camera on a rail is impractical. Camera's CCD sensor in a forward-facing camera should have resolution of at least 3500x625 pixels and be capable of a scene capturing with a speed of at least 30 frames per second. Such CCD, even if available, needs special care and is rather pricey. One known solution is to translate the smaller CCD in the camera itself as the camera itself translates on a rail. But, not only does this require making a specialized camera and an extremely precise movement of the CCD, but also the resulting image is necessarily severely distorted by the needed extremely wide FOV lens.

We therefore needed to find a novel and effective solution to this image capture problem, preferably by using widely available photo or video cameras. Our HoloCam [8,9] is a portable system that comprises a stepmotor-controlled translating digital camera mounted on a 1 to 4 meter horizontal rail. Camera is moved on this horizontal rail and at the same time it is using a rotational electromechanical stage. The video camera (or photo camera working in video mode uses a narrow FOV lens with zoom-in zoom-out function. A special controller controls camera rotation and translation movements. We use a novel numerical algorithm to transform the data obtained from the camera to produce high-resolution distortion free data of a format that is required by modern printers (i.e. data produced by a wide FOV purely translating camera). Results from our system clearly show it to be a superior method to the prior art, and it is capable of producing fundamentally better holograms. The simplicity of the solution also means that HoloCam is portable and, for static objects, even several HoloCam systems can be linked together to shoot bigger objects, like buildings, trees, trucks, etc..

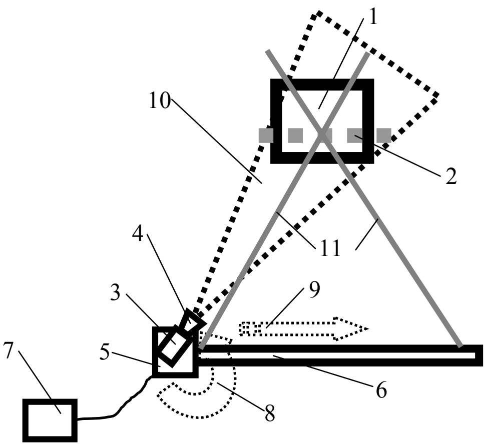

Fig. 10 A diagram of the HoloCam system - 1. The object to be recorded; 2. Future hologram image plane; 3. Digital camera at the left-most position at the electromechanical stepper-motor rail; 4. Camera zoom objective; 5. Stepper-motor precision rotation stage; 6. Electromechanical stepper-motor rail; 7. Rotation stage and translation rail controller; 8. Digital camera angular movement; 9. Digital camera linear movement; 10. FOV of the digital camera; 11. two laser pointers beam.

Fig.10 shows a diagram of the HoloCam system. The scene to be recorded is placed at a certain distance from the rail. Two laser pointers fixed at the rail edges are angularly adjusted in such a way that their intersection point is in a place where future hologram image plain will be. The scene to be recorded is positioned in such a way that desired scenes' parts would be recorded to appear in front or behind future hologram image plane.

Given the distance of the frame from the camera track (h), the hologram width (D) (= the frame width) and the horizontal FOV (θ) required by the hologram printer of an ideal purely translating camera, the camera tracking length may be calculated (Fig. 11.). The half of the required camera track length is given by

$$T = 2h\tan(\frac{\theta}{2}) - D \quad (1)$$

The rotating camera should move at a constant velocity from one end of the rail to the other. Whilst the camera is moving, the rotational stage is activated continuously so that the camera always targets the center point of the frame. The camera takes pictures at regular intervals. When the camera has finished taking pictures images data are transformed using a special algorithm.

The operation of the camera can be realized in two different ways. One method (Still) is to synchronize the camera's shutter to each particular camera position on the rail. Another method (Movie) is to use a continuously filming camera and start filming when the linear velocity of the camera is constant. Both methods have their advantages and disadvantages. By synchronizing the camera shutter to each particular point on the rail more precise pictures are taken, but this is slower compared to continuous shooting. On the other hand, the Movie method allows us to use conventional digital movie cameras in our HoloCam systems – resolution of nowadays cameras allows to capture life scenes for digital holograms in size of up to 100x150cm.

Both camera movement control methods have been physically implemented in both HoloCam models – Portable and Studio. The difference between models is in linear translation rail length and external computer usage. Portable HoloCam uses external computer only for captured video future hologram preview and video scrambling for sending it via Internet to the printing facility. In HoloCam studio computer screen is also used for scene setup by observing on it leftmost center and rightmost images of scene to be shot.

The key difference of our image transformation method is that instead of usual keystoning, each pixel of shot video frame is transformed in virtual three-dimensional space to the pixel with same coordinates that would be taken with the translated-only video camera.

3. Lighting

Digital holograms usually have horizontal parallax only (HPO holograms). That is related mainly with computing power needed to calculate information that will be written in one holopixel. Images used for HPO holograms are shot while camera moves straight in front of the object. Therefore, information of how object looks from above or beneath is not present on such images. For full parallax holograms camera should make a significantly bigger amount of shots, which is hardly possible for the live scenes and takes a lot of computing time for digitally modeled scenes rendering.

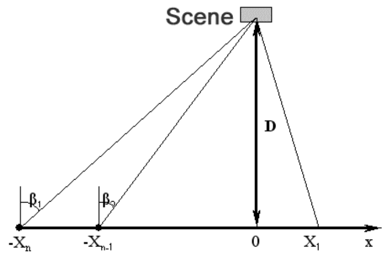

Fig. 11 HOLOCAM camera movement

Practical disadvantage of the full parallax digital holograms is one powerful point light source that is needed for their illumination. In 1989 year there was proposed a solution for full parallax hologram lighting which included several concave mirrors that were forming the light beam in such a way that it would correspond to illuminated hologram square shape [10)]

However, such hologram illumination method is hardly implemental and big format hologram illumination would require quite powerful point light source. But for one parallax hologram illumination several light sources can be used. The only requirement is that those several light sources would be placed in one line on a plane, which is perpendicular to the parallax direction. I.e. if we want to light horizontal parallax hologram, the light sources shall be placed in vertical plane (Fig. 12, left).

This lighting method of HPO holograms allows to achieve great brightness with several inexpensive light sources. However, as it is seen from Fig. 12., left – quite

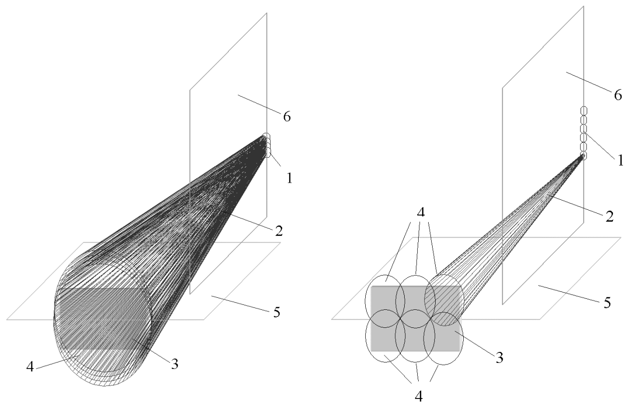

Fig. 12. Conventional (left) and new (right) HPO hologram lighting solutions. 1 – several light sources; 2 – light cone; 3 - HPO hologram; 4 – illuminated area; 5 – hologram parallax plane; 6 – light sources plane.

noticeable part of the light is not hitting HPO hologram surface and is simply wasted.

Our solution to this HPO hologram lighting task [11)] is placing light sources on a flexible holders, which allow to change each bulb light direction independently in such a way that all lamps filaments remain on a straight line – Fig. 13.

Our lighting solution allows to use lamps with narrower lighting angles and to illuminate different HPO hologram parts separately (Fig. 12., right) thus increasing the light usage efficiency and achieving greater HPO illumination with the same amount of light sources used. Since usual light sources used for hologram illumination (halogen bulbs, projectors) have Gaussian light intensity distribution, there is a possibility to overlap areas lighted by each lamp achieving almost even hologram surface illumination.

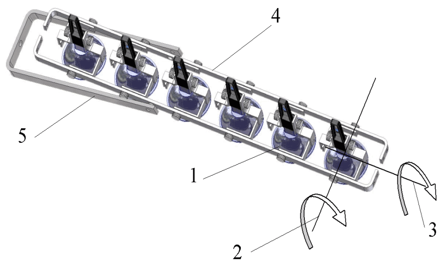

Fig. 13. Geola HPO hologram lighting lamp. 1 – halogen bulb; 2 – bulb' horizontal rotation axis goes through bulbs filament; 3 – bulb' vertical rotation axis goes through bulbs filament; 4 – holder/electrical connector; 5 – lamp fixture.

4. Digital reflection holograms as autostereoscopic screens

We have investigated reflection holograms possibilities to act as autostereoscopic screens [12)]. Any illuminated reflection hologram having image elements that appears in front if the image plane, sends the light to form those image elements. This reflection hologram ability to redirect its illumination light into certain places in space can be used for autostereoscopy needs. In the digital hologram case, it is quite easy to print reflection holograms with desired characteristics.

Fig. 14 illustrates reflection hologram (3) ability to send the point source (1) light (2) for holographic image (6) formation in front of the hologram. When observer is at the position (7), which is far enough from hologram surface – he sees holographic image element (6) hanging in space in front of the hologram. But when observer's eye is placed at position (6), which is near or inside this holographic image element – it sees holographic media surface that sent light to form said image element as shining area on holographic media surface.

It is possible to make a reflection hologram, which has said image element replaying at a greater distance from hologram surface – 0.3÷2.5m, depending on hologram size. In this case, the whole holographic media surface will participate in this image element formation and viewer in position 6 will see shining area filling whole holographic media surface.

Let's see what will happen when two light sources are used for reflection hologram illumination – Fig. 15. Two light sources will cause two holographic images formation in space. Now, if holographic image element (5) size is bigger that human eyeball and smaller than average distance between human eyes, it is possible to find such light sources' distance between each other such that both observer's eyes at position 6 would see hologram surface illuminated by only one light source. Fig. 15. shows how holographic image elements (5) and (5') are formed by light sources (1') and (1) respectively.

Since reflection hologram allows viewer to see hologram surface illuminated by two light sources in such a way that each of the two eyes sees only one light source illumination – reflection hologram can be used as autostereoscopic projection display.

When for hologram illumination two video projectors are used as light sources, and projected images are focused on hologram surface, each viewer's eye in position (6) will see image projected by different projector. If projectors will project a stereo image pair, viewer shall percept the projected stereo image pair as a three-dimensional scene.

Holographic autostereoscopic projector implementing this reflection hologram feature was assembled in our laboratory. As screen we have used digital reflection hologram in size of 64x48cm. The hologram contained one image of white vertical stripe appearing at the distance of 100cm from holographic media. Two usual video projectors were placed in a space on top of the hologram in such a way that hologram would be illuminated and replayed images appear bright and colour-balanced. Video projectors were connected to conventional PC having video card with two independent outputs and independent image keystoning for each output. Our experimental autostereoscopic projector setup is shown on Fig. 16.

Best results were obtained with projectors that are 13 cm apart, each projector set with the required keystoning compensation to display a rectilinear image. 3D scene was perceived within a 15 cm depth viewing zone at the distance of 100 cm from holographic screen surface – i.e. viewer is not strictly bounded to certain distance from holographic screen, which is the case for majority of autostereoscopic screens based on holographic optical elements. Photograph of holographic image element's appearance in front of the holographic media while two video projectors illuminate hologram is shown on Fig. 17.

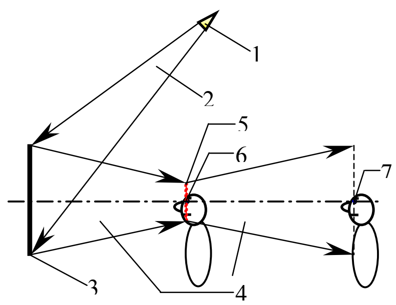

Fig. 14. Reflection hologram with image element replaying in front of the holographic media.

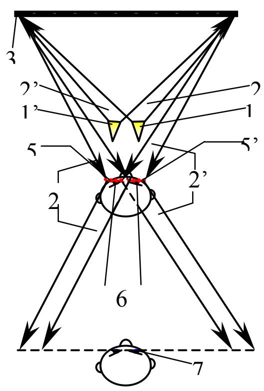

Fig. 15. Reflection hologram with image element in front of the holographic media. Hologram is illuminated by two light sources and two image elements are visible.

Autostereoscopic effect was clearly observed without any additional aid of polarized glassed and/or other devices. Stereo image pairs were standard pairs used for conventional autostereoscopic projectors operating with polarized glasses. Also we have experienced 3d viewing of usual 2D video stream converted to stereo pair stream using TriDef Media Player software. Also we had projected the images from a pair of video cameras set at the intraocular distance (i.e. the distance between human eyes). In such a manner we have observed live moving three-dimensional images, which proves that this setup also can be used as 3D television set.

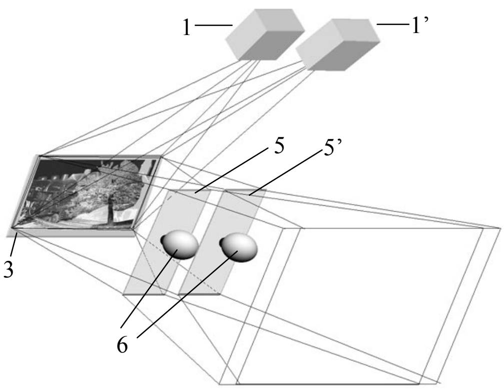

Fig. 16. Autostereoscopic image projector setup

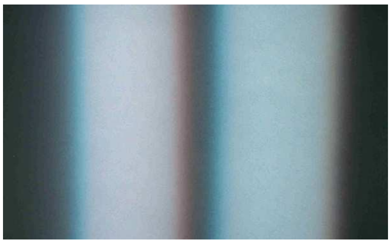

Fig. 17. Photograph of reflection hologram image element's appearance in front of the holographic media while hologram is illuminated by two video projectors – projection at white screen placed at a distance of 1m from hologram surface.

The efficiency of our holographic screen was evaluated by placing a digital spectroscope sensor at a distance of 100 cm from the screen inside holographic image element forming zone, measuring reflected light intensity and comparing it with intensity of the light directed to same place by usual white screen with 75% reflectivity. We have also evaluated ambient light influence to holographic screen reflecting properties. For that holographic screen was additionally illuminated from side with halogen light projector giving the parasitic light intensity of 15kLux on holographic screen surface. The measured spectrums are shown on Fig. 18 and summarized in the table 4.

Measurement results show that holographic autostereoscopic screen has better noise/signal ratio than conventional white screen. While holographic autostereoscopic screen is less reflective than conventional white screen, it is also less sensitive to parasitic ambient light, which always affects the performance of a projection screen and reduces projected image's perception quality. Bigger holographic screen reflectance can be achieved by using video projectors, which light sources would have maximum light emission at the wavelengths corresponding to hologram replay maximum wavelengths.

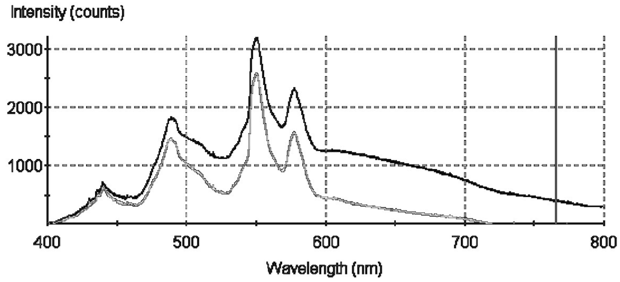

Fig 18a Reflection spectrums of white screen illuminated by digital image projector only (gray) and by digital image projector and white sidelight (black).

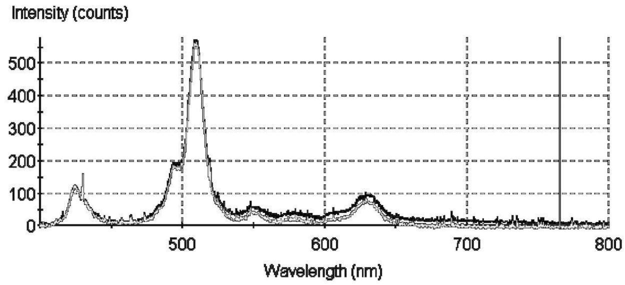

Fig 18b Reflection spectrums of white screen illuminated by digital image projector only (gray) and by digital image projector and white sidelight (black).

Table 4. Holographic autostereoscopic screen versus white screen with 75% reflectivity

	Holographic autostereoscopic screen			White screen			
Reflected projector's light picks wavelengths, (nm)	425	513	627	440	490	550	575
Reflection without side light Intensity (counts)	120	560	38	625	1450	2575	1550
Reflection with side light Intensity (counts)	120	565	48	725	1850	3150	2300
Noise/signal ratio	0%	1%	20%	14%	22%	18%	33%

Since the image pairs, projected to holographic screen are formed digitally, it is possible to add additional service image pairs. For example, there is possible to add control panel that will be percepted by a viewer as hanging in the air in front of the screen. Using remote movement detectors attached to the screen such panel can be used to operate the viewing device, or to control remote processes observed through viewing zones.

Using remote head tracking system attached to the screen, it is possible to obtain exact coordinates of the viewer and direct projectors' lights in such a way, that viewing zones to the certain extent would be matching viewer's position in space.

We have investigated a possibility to use such holographic screen for more than one user. It was found that such screen with just one white stripe imprinted could be used for two viewers by placing additional pair of projectors. More research is needed for further increase in viewers' number.

Big reflection hologram advantage in autostereoscopy is that image projectors can be placed at any distance from screen surface (in holographic optical elements case, projectors shall be at a certain fixed distance from screen). Maximum autostereoscopic screen size, which we can achieve on current photomaterial, is 100x150cm, so it can be used in numerous 3d applications for one or few viewers.

We also have investigated a digital reflection hologram containing just flat white field imprinted at the image plane. This hologram has showed similar noise/signal ratio and can be used as usual projection screen at high ambient light level conditions.

5. Conclusions

Complete range of necessary equipment and materials for digital holography has been developed.

Full colour digital holograms can be printed and copied with speed needed for industrial applications.

Life scenes can be easily captured for their imprinting in digital hologram form.

Digital holography can be used for autostereoscopic projection screen manufacture.

Digital holography can be used for full colour security hologram production.

Digital holograms copying method probably can be used for holographic ROM copying.

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