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RECENT WORKS ON DIRECT-WRITE DIGITAL HOLOGRAPHY

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Direct-write digital holographic (DWDH) printing is a highly flexible technique for the generation of photoresist masters, which are required to produce the metallic shims used for the mass production of holograms in the security and packaging industries. Here we describe a new type of holographic feature, which can be combined with any other feature printable using DWDH: full-parallax, full-colour transmission masters containing limited animation. We will also describe a technique to print the fringe pattern of each hogel without using a reference beam. By programming the required fringe calculation algorithm on a graphics card using CUDA, we obtain acceptable calculation times. The advantage of using such direct fringe writing is that once again DWDH allows extra features to be written onto a master and combined with other features to produce a stronger security solution. Finally, we present results concerning the use of hogel image dithering to improve the grey-scale performance of DWDH printers.

Keywords: *Digital hologram, direct-write holography, DWDH, image-matrix lithography, holographic printer, photoresist, security holography.*

1. INTRODUCTION

The technique of writing digital reflection holograms as a matrix of small adjacent elemental holograms (now known as 'hogels') was first demonstrated by Yamaguchi et al. [1] (JP) in 1990. These early experiments, although monochromatic, slow, and employing contact apertures, led the way to the development of what is today known as DWDH or Direct-Write Digital Holography [2], [3]. In the late 1990s, Klug et al. (USA) working at Zebra Imaging Inc and Brotherton-Ratcliffe et al. [4] (LT) working at Geola UAB improved Yamagushi's technique to allow the production of large-format high-quality full-colour reflection holograms having relatively large hogels (0.8 mm–1.6 mm). DWDH was subsequently developed at Geola Digital UAB (LT) by Stanislovas Zacharovas et al. [5]–[9] to produce high-resolution digital master holograms for security applications. Here the hogel size was reduced to 100 microns, and photoresist was used as the recording medium. This work has led directly to the recent availability of commercial security mastering machines known as DIWO (Direct Write Originator), which complement the well-known techniques of E-beam [10], Dot-Matrix [11]–[13] and Image-Matrix or Kinemax [14] technology, currently in use by much of the holographic security industry. The combination of DIWO technology with Image-Matrix Lithography and a fast blue pulsed laser allows the rapid writing of all security features from Level 1 to Level 4 in a security master including achromatic and deep 3D HPO colour images with covert optical security features.

2. EXPERIMENTAL

Current DWDH security origination is commercially available through Geola's DIWO-6 originator (Fig. 1). This machine typically uses a DPSS SLM 440 nm blue pulsed laser operating at 30–120 Hz for fast origination of security masters, employs a sequential inscription of holograms, each comprising an ensemble of elemental parts called hogels or holopixels (Fig. 2).

As in all DWDH systems, the hogel constitutes a fundamental holographic optical unit akin to a pixel in a digital image but differs by offering varying visual representations from different viewing angles, paralleling the behaviour of conventional analogue holographic elements. Given the limitations of the human eye in discerning small detail, the selected size of the holographic unit (hogel) for master-original printing in DIWO-6 is chosen to be 100 x 100 microns. This dimension allows for the projection of extremely high quality distinct visual perspectives depending on the viewing angle. The underlying mechanism of the recording scheme is depicted in Fig. 3.

The high numerical aperture Fourier-Transform objective lens used by DIWO-6 projects a focal point beyond its physical extent. Around this focal spot, light beams emitted from each pixel on a Spatial Light Modulator (SLM) maintain a near identical size and directional consistency. Introducing a reference beam to this focal point allows for the inscription of a hogel as a holographic optical element that, when illuminated, directs light beams along the paths established during recording.

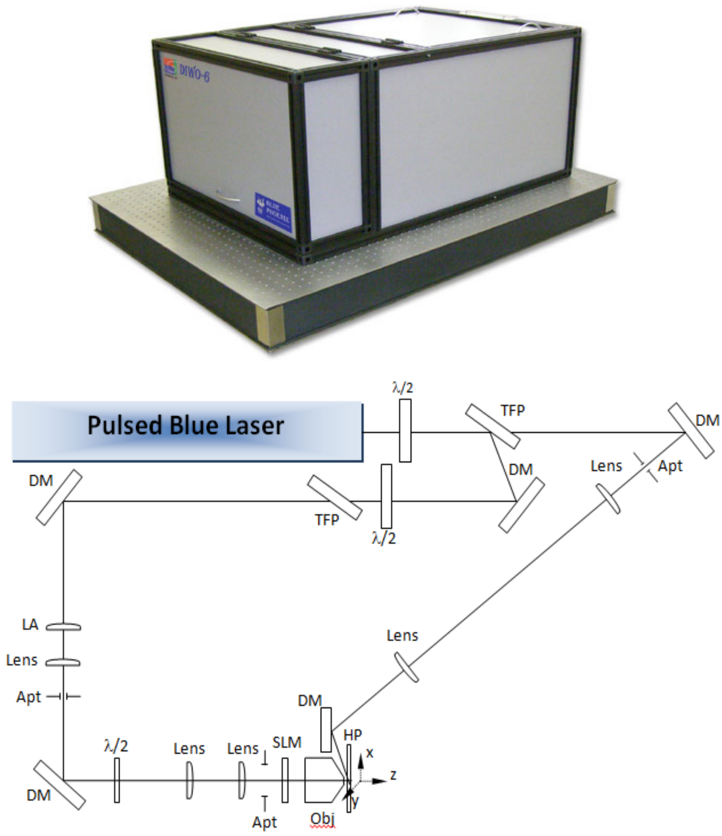

Fig. 1. DIWO-6 DWDH Originator (above) and simplified optical scheme (below). DM = dielectric mirrors, TFP = thin film polarizer, λ/2 = half wave plate, SLM = spatial light modulator, Obj = Fourier transform objective, Lens = lenses, Apt = aperture, LA = lens array, HP = holographic plate.

For the generation of the SLM image required for the inscription of each specific hogel, Geola employs a collection of parallax-related 2D images of the 3D scene, captured from various viewing angles along a horizontal line (either using a moving digital camera for real world scenes or a virtual camera in CAD software). Corresponding pixels are extracted from each 2D parallax-related image and merged into a new "pixel-swapped" image displayed on the SLM. When illuminated, each hogel then replays these 2D pixel images at their corresponding angles. The viewer's binocular vision interprets these parallax-related 2D images as a 3D scene (HPO – horizontal parallax only).

An HPO hologram of a 3D object produced using this method usually contains 200 to 800 parallax-related views, thus eliminating any unwanted image transition effects, unless intentionally introduced. This streamlined holographic recording process can swiftly yield effects unachievable with other origination techniques. These include high-resolution 3D images that are:

- bright and highly diffractive;
- capable of motion replay;
- deep;
- colour-rich;
- grayscale;
- mixed grayscale and colour;
- front and back illuminated grayscale and colour (for transparent films).

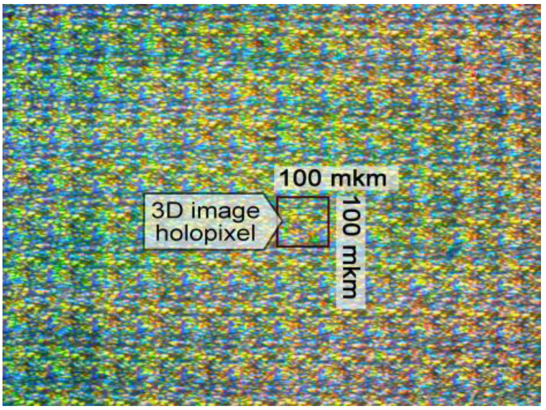

Fig. 2. Microphotographs of an embossed 3D image hologram originated with Geola's DIWO-6 – Direct Write Originator. Note that the hologram is made up of a raster of 100 micron x 100 micron hogels.

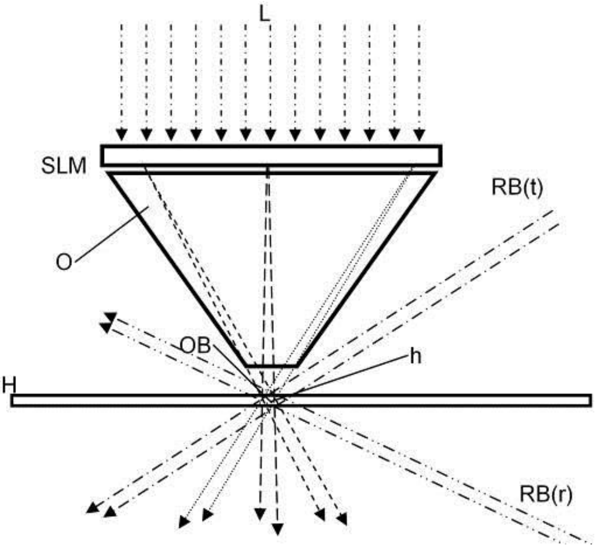

Fig. 3. Writing a hogel for a DWDH hologram. L – the laser beam, OB the object beam, RB(t) and RB(r) – reference beams for transmission and reflection holograms, respectively; h – a hogel, H – the white-light reflection or transmission hologram.

3. RESULTS AND DISCUSSION

3.1. Full-Parallax Optically-Variable Achromatic 3D Images now Available in DWDH Originators

Traditional dogma dictates that reflection holograms are able to support the display of full-parallax images, but transmission holograms must sacrifice the vertical parallax in order to avoid image blurring (as dispersion is much higher in the vertical dimension). Whilst this dogma is certainly true in principle, dispersion of a full parallax DWDH hologram of vanishingly small depth is zero. In fact, the dispersion in the vertical dimension of a hologram with a moderate reference angle (e.g., wall-mounted) only blurs the holographic image unacceptably after a small but finite image depth. In the context of small security and packaging holograms, it turns out that the critical depth available is enough to support optically-variable full-parallax achromatic images with acceptable blurring. Practically this technique can be implemented on existing DIWO-6 machines with only a software upgrade. The technique consists of using a standard full-parallax animated dataset for the required achromatic scene (as used in standard DWDH full-colour full-parallax printers) and using the calculated SLM images as data for the DIWO-6's unique SLM. Figures 4 and 5 show an animated watch hologram produced with the new software created for the DIWO-6. By moving the hologram around in your hands, the image appears clearly full-parallax and in addition the watch hands rotate around the clock face. This feature is a distinct improvement over the HPO images available previously as moving the hologram simulates a real watch. Previous HPO holograms available on photoresist masters showed no motion or parallax change with a vertical tilting of the hologram and as such did not correctly simulate objects such as a watch with moving watch hands.

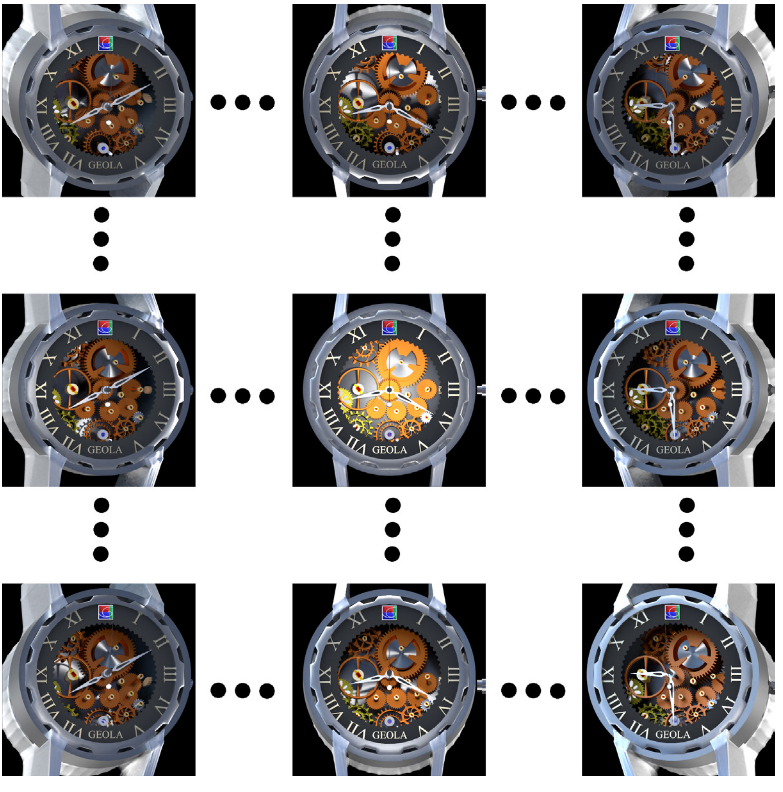

Fig. 4. Full-Parallax Perspective View Renders of the hologram of Fig. 5. Note that the position of the watch hands are arranged so that as the viewer tilts the hologram up and down and left to right, the hands rotate around the watch face.

Fig. 5. Full-Parallax Optically-Variable Hologram Labels (Left) and Master (Right). Digital DWDH Master made using DIWO-6 originator on photoresist.

3.2. Improving the Greyscale

One of the issues up to now of writing DWDH holograms onto photo-resist at the extremely small hogel sizes used in the DIWO-6 has been a less than optimal greyscale. Geola has now released a new software version for the DIWO-6, which significantly improves image greyscale. This has been done using a post-processing of the SLM images using Burke's algorithm for dithering. Since the DIWO-6 employs 100 micron hogels, its high-resolution SLM cannot be resolved on replaying the hologram due to digital diffractive blurring [2]. As such dithering the SLM images at the full resolution of the panel produces no angular degradation of the images. However, as with standard 2D dithering, significant improvements to greyscale are observed.

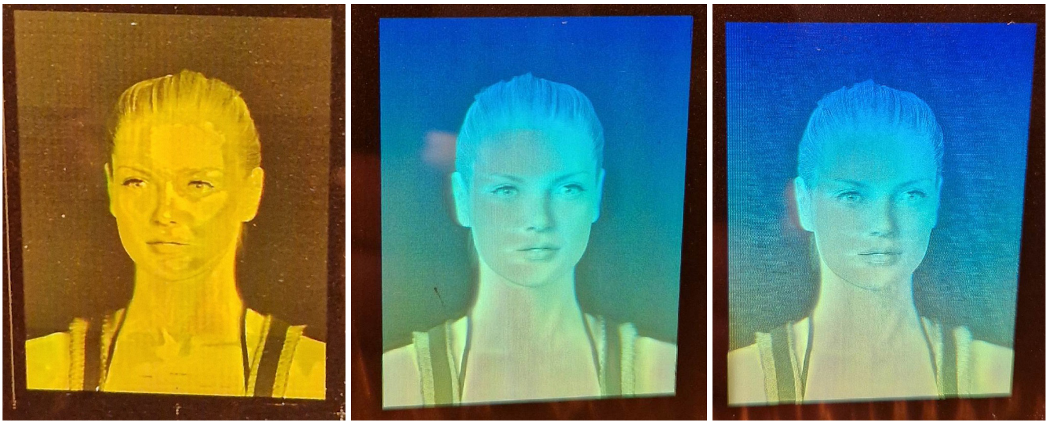

Fig. 6. Hologram recorded without Dithering (Left). With Dithering on Perspective View Images (Right). With Dithering on SLM Images (Centre).

Typical results are shown in Fig. 6 where on the left a hologram recorded without dithering can be seen. The poor greyscale is clearly visible as patches on the girl's face and chest. The centre photograph shows the result of dithering the SLM images using Burke's algorithm. Not only is the greyscale substantially improved, but importantly there is absolutely no spatial image deterioration. As a comparison, the effect of dithering the raw perspective view images is shown on the right-hand image. Here we can see a clear improvement of the greyscale but at a cost to the spatial resolution.

3.3. Image-Matrix versus DWDH

Geola offers two types of security origination systems: the DIWO-6, which has been described above, and the IMP-6, which is an image matrix machine. The two machines are designed to be complimentary, and master holograms can be written and over-written on both machines. Together these machines allow all security features covering level 1 to 4 to be produced on the same master (see Figs. 7 and 8). The IMP-6 has two modes of operation – holographic and lithographic. These modes are switchable in real time, and so different parts of the shim can use different methods of operation. The highest resolution obtainable is 210,000 dpi. Complex optical security features with holographic images of shallow depth can be printed with the IMP-6 at moderate speed. The DIWO-6 adds deep holographic imagery at faster speeds.

Visibility	Verified by	Diffractive effects and elements	Level
Public (Overt)	Customer	True colour, 2D/3D, Bass-relief, E-beam motion, Guilloches, Lenses, Compass,	Level 1
Simple Aided verification (Obvious)	Specialists	Microtext, Smart glint, Letter lens, Laser readable image, ets	Level 2
Not obviously visible (Covert)	Inspectors	Nanotext, ets.	Level 3
Invisible without very special equipment	Forensic labs	Forensic features (holoframe size, shape, spacing, internal structures of the holoframe, grating period and angle, noise	Level 4

Fig. 7. The various levels of security features used in modern security holograms.

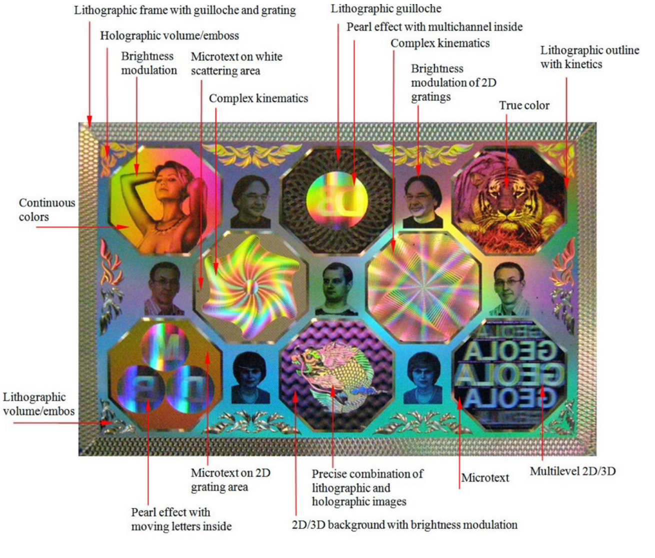

Fig. 8. Diffractive features producible by IMP-6.

3.4. Writing DWDH Holograms Using the Image Matrix IMP-6

Currently, in order to print deep holographic images on a security master, including the optically variable full-parallax holograms described above, a DWDH printer such as the DIWO-6 is required. We report here of our first attempts to print DWDH holograms on the image matrix machine IMP-6 using software data processing to calculate the interferometric fringe pattern of individual hogels. These fringe patterns are then imaged directly onto the photoresist using a 405nm laser. In the DIWO-6, the fringe pattern of the hogel is produced by the interaction of a reference and object beam.

The fringe pattern calculation is based on the fact that each DWDH hogel on replay essentially projects a 2D image of the recording SLM mask. The distance of the focal plane of this projection from the hogel is usually arranged to be in the range of the optimum viewing distance to infinity. A Fourier or Fresnel transform (as the case may be) of the SLM hogel data, therefore, defines the fringe pattern of the hogel.

Early attempts to calculate the hogel fringe pattern using Matlab and Fortran required a prohibitively long time. Due to the complexity and size of the fringe calculation, we, therefore, coded the calculation using CUDA, which then brought the calculation time down to a reasonable range on a small PC. As an example, Fig. 9 shows full-parallax perspective view data, which has then been converted to hogel fringe data as illustrated in Figs. 10 and 11.

The final hologram is shown in Fig. 12. It must be emphasised that this is the first test only and as such the quality of the hologram is not optimal. We are, however, optimistic that the quality can be significantly improved; as such DWDH holography features may plausibly be integrated into the IMP-6 in future generations.

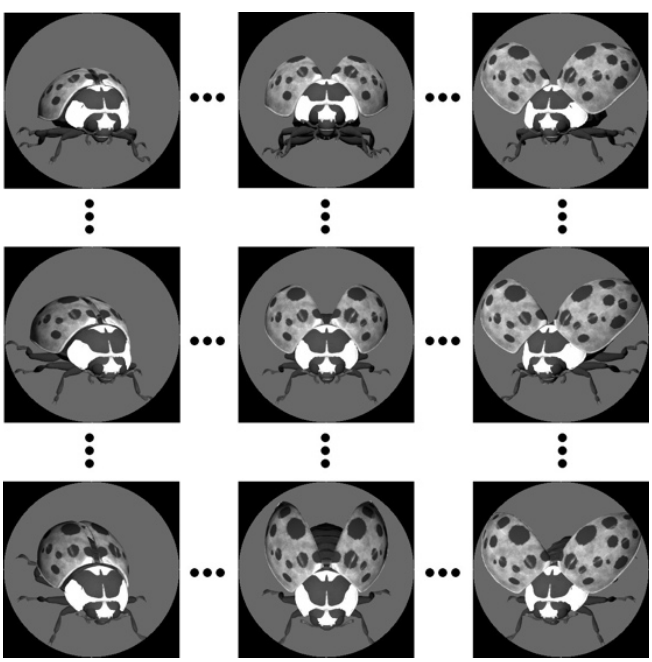

Fig. 9. Full Parallax Perspective View Data used to calculate DWDH hogel fringe patterns for subsequent lithographic inscription using the image matrix machine, IMP-6.

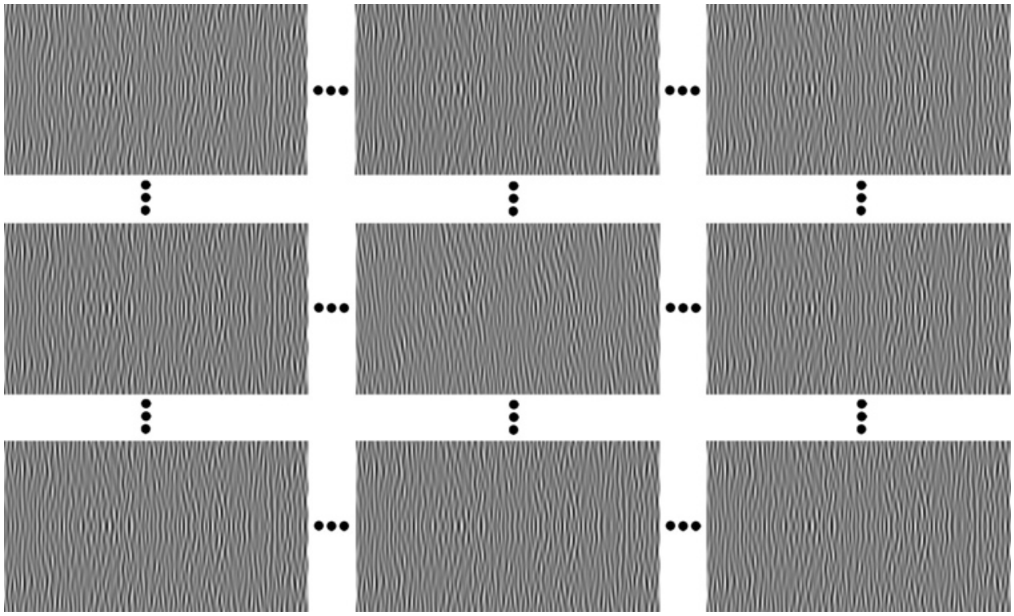

Fig. 10. 300 x 300 hogel fringe images calculated by a CUDA algorithm using the data of Fig. 9. This fringe data is then used by the IMP-6 to produce a 3cm x 3cm full-parallax achromatic transmission hologram master composed of 300 x 300 hogels, each of 100 micron diameter.

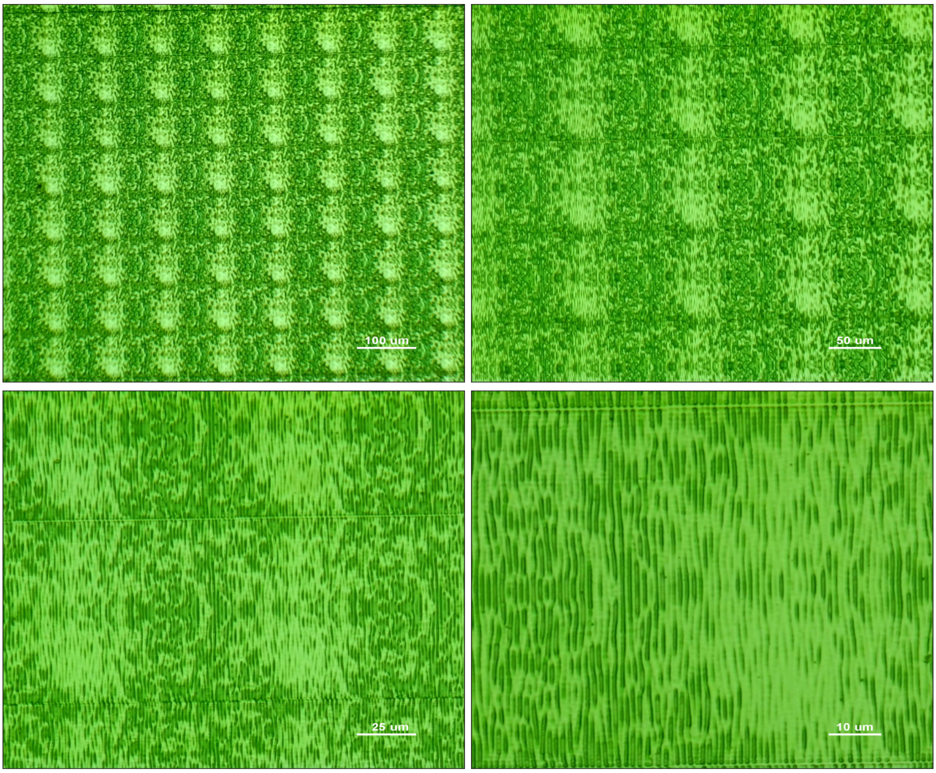

Fig. 11. The structure of a hologram consisting of DOE pixels at different magnifications. Images obtained using a metallurgical microscope under narrow band of green illumination.

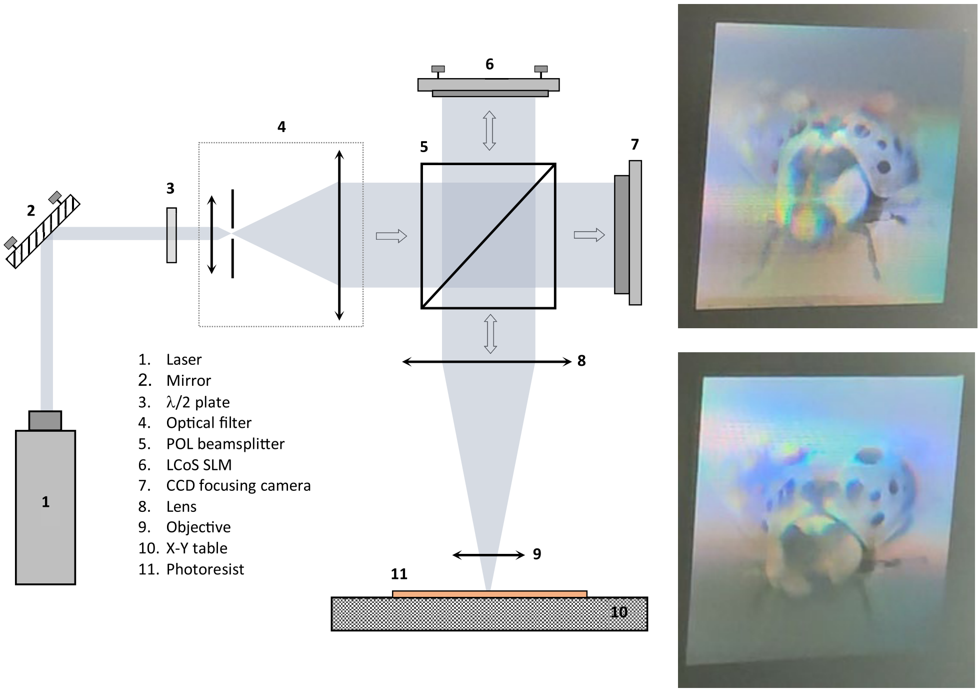

Fig. 12. (Left) A simplified scheme and photo of optical lithographic system used in recording the DWDH fringe patterns above by the IMP-6. (Right) Two views of final recorded hologram.

Fig. 13. For comparison this is a hologram of the data of Fig. 9, produced on a DIWO-6 machine.

4. CONCLUSIONS

We have presented two new features that are now available as standard in Geola's DWDH commercial security originator DIWO-6. These are:

- the inclusion of full-parallax achromatic optically-variable stereograms on a security photoresist master and
- the improvement of greyscale on all holograms created by the DIWO-6 machine using dithering of the SLM images by Burke's algorithm.

We have also presented initial work concerning the creation of true DWDH security hologram features using the image matrix IMP-6 machine employing only lithography. Here the DWDH fringe pattern of each hogel is calculated via computer rather than formed by interference. Initial results are promising; further work will be required to see whether the image quality can be increased to a satisfactory level.

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