21. Дифракционные структуры поверхностного рельефа для массового производства прозрачных голографических экранов

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Прозрачные экраны уже применяются в автомобильной промышленности для проецирования информации важной для автоводителей. Большинство таких экранов изготавливаются голографическими методами, с использованием фотополимеров в качестве регистрирующей среды. В результате стоимость производства таких экранов является высокой, что, в свою очередь вызывает применение таких экранов только в автомобилях высшего ценового диапазона. В результате нового подхода к решению проблемы, прозрачный голографический экран был изготовлен как прозрачный поверхностный рельеф на прозрачной подложке, обладающий свойством направлять проецируемое на него цветное изображение в угол обзора достаточный для его восприятия водителем автомобиля, и, в то же время, не мешающий ему воспринимать происходящее за экраном. Экран был напечатан на пилотном Оригинаторе Геолы Blue Phoenix DIWO-6 на фоторезисте как поверхностный рельеф воспроизводящий ахроматическую голограмму плоского экрана. Голограмма была записана разработанным Геолой методом Прямой Записи Голограмм. В статье объяснен метод производства мастер-голограммы прозрачного голографического экрана пригодной для тиражирования методом тиснения.

Ключевые слова: Автомобильная промышленность, Прозрачный экран, Голографический оптический элемент, Оригинация тисненых голограмм, Ахроматическая голограмма.

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Diffractive surface relief structure for the see-through screens mass replication

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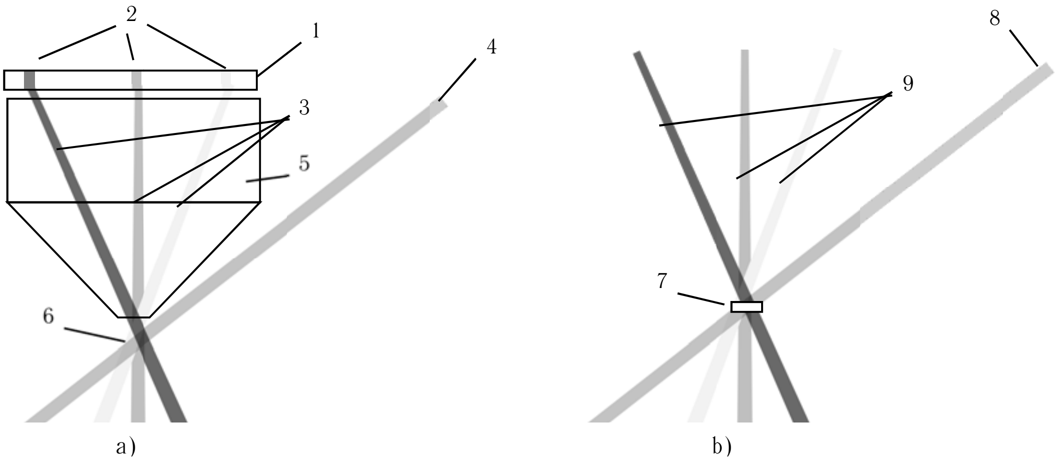
The automotive industry is already using see-through screens to project onto them various information important to the drivers. Majority of such screens are manufactured holographically, employing photopolymers as a medium. As a result, the costs to produce said screens are rather high which limits their applications to higher priced cars only. A novel approach to produce such a screen as surface relief hologram was used and the holographic optical element behaving as see-through screen with viewing angle covering the driver's seat was manufactured. The screen was printed with Geola's Blue Phoenix DIWO-6 pilot hologram originator on photoresist as achromatic surface relief hologram employing direct hologram write method. Article explains said direct hologram write method and the diffractive see-through surface relief production. Such surface relief then can be mass-replicated by embossed holography means.

Keywords: Automotive industry, See-through screen, Holographic optical element, Embossed hologram origination, Achromatic hologram.

Introduction

There are several approaches to produce see-through displays for car drivers. Some of them employ holographic methods to produce screens diffracting visual information towards desired direction [1, 2], others employs transparent LCD displays, or even transparent medium embedded with nanoparticles that selectively scatter light at the projected wavelength and on which monochromatic images are projected [3]. See-through screens which are mass-produced employing holographic light directing methods are produced using photopolymers as photosensitive media. Photopolymers perform well in this domain, but photopolymeric mediums itself have rather higher price tags and production of see-through screens with those photomaterials requires their exposure with laser radiation as well as pre- or post- exposures with non-coherent visible or UV light; sometimes also additional heating is required after photopolymer exposure [4].

Photopolymer layer on photopolymeric medium is usually protected with polyester film, which shall be removed before the exposure — that makes hologram recording process on this medium more complicated than that on conventional Silver Halide photomaterials. Nevertheless holograms on photopolymers can have diffraction efficiency of up to 90 % [5] and, once polymerized, photopolymer does not change its volume, nor is affected with direct sunlight. Holograms on panchromatic Silver Halide photomaterial can reach 38 % diffraction efficiency [6] but, since this photomaterial is Gelatine-based, are sensitive to humidity and temperature changes which make them not really good choice for the outdoor applications. But there is another medium where diffraction efficiency of the diffractive structures can reach 60 % — this medium is a high quality embossed holograms [7]. Such embossed holograms also can be transparent and that would make them a perfect medium for low-cost see-through screens for outdoors applications.



1 — SLM, 2 — SLM pixels, 3 — modulated laser radiation beams (object beam), 4 — not modulated laser radiation beam (reference beam), 5 — Fourier objective, 6 — objective waist, 7 — hogel, 8 — illuminating light, 9 — light diffracted by hogel

Fig. 1. Hogel recording (a) and replaying (b)

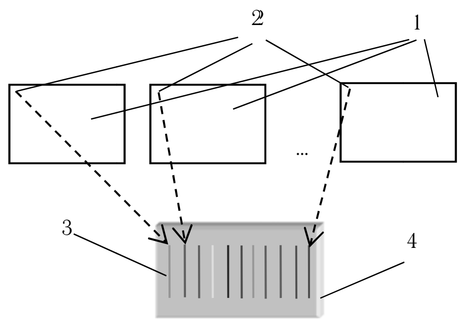
The key point for the embossed holograms manufacturing is the origination — i. e. creation of the original diffractive structure as surface relief on a plate coated with organic [8] or inorganic photoresists [9]. That relief, which is essentially a White Light Transmission (WLT) hologram, then is duplicated onto nickel shim that is used for replicating of said relief by embossing on polyester film. The film with embossed relief is ether coated with thin metal layer, or left transparent [10]. Embossed holograms manufacturing is a well-developed industry and this transparent embossed holograms indeed could be used as see-through screens, if only the directional and panchromatic light-scattering surface relief would be available. One of the methods of such relief production is Direct Write Digital Holography.

1. Direct-write digital holography

Direct-write digital holography or *DWDH* was developed at the end of the 1990s and the most frequently cited article in the field is Yamaguchi et al [11] (1995). But many other people and research groups participated in the development of this hologram printing method. As early as 1990 Steve McGrew had patented a device called ‘Holocomposer’, which was able to produce small format direct-write holograms for high-security ID cards [12, 13]. In 1991 Stephen Benton had produced probably the first large direct write stereogram, which he called an ‘Ultragram’ [14]. Even as early as 1987 Kenneth Haines had outlined the principles of a direct hologram write technique [15]. In 1998 Klug et al [16], working at Zebra Imaging, extended the technique to the manufacture of large format full color full-parallax reflection holograms. In 1999 Brotherton-Ratcliffe et al. [17] demonstrated that the technique could be made to work much faster and more reliably using pulse RGB lasers. And finally in 2013 Zacharovas et al. adapted this technique to embossed holograms origination employing as coherent radiation source the pulse laser specially developed for this purpose [18].

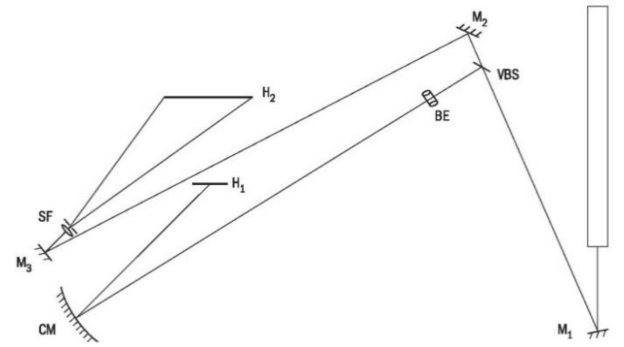
Direct-write digital holography is described in details in the literature [19, 20], so here we will just briefly mention that DWDH hologram is actually the entirety of small digital holographic elements called *‘hogels’* or *‘holopixels’*. Each hogel acts as pixel on electronic display — while illuminated by light source it diffracts light of certain pre-defined intensity and colour. The difference from electronic display pixel is that hogel projects different pre-defined light intensities into different pre-defined viewing angles. That enables one to construct from hogels a medium which will act just like classical analogue hologram: will contain image viewed differently from different viewing angles. And if the hogels are small enough and quantity of parallax-related images used to program hogels intensities into different viewing angles is big enough — observer will not be able to distinguish between digitally printed hologram and hologram produced with analogue holography methods.

Hogels are recorded by intersecting two square form laser radiation beams onto photosensitive layer where their interference image is recorded. One of the beams is modulated with Spatial Light Modulator (LCD, LCOS) i. e. acts as object beam, another beam is not modulated and acts as reference beam. The modulated object beam before interaction with reference beam passes a special objective which has its optical waist outside its body. Each



1 — 2D parallax-related images of 3D scene,
2 — series of pixels having the same coordinates;,
3 — SLM, 4 — image as displayed on SLM

Fig. 2. Hogel image formation on SLM: (a) for a digital holographic print with horizontal-only parallax



H1 — master hologram, H2 — photosensitive medium where White light transmission hologram will be recorded, BE-spatial filter–cylindrical lens combination, CM — collimating mirror, VBS — variable beam splitter, M_1–M_3 — mirrors.
Fig. 3. Standard table arrangement for a H1–H2 holographic image transfer

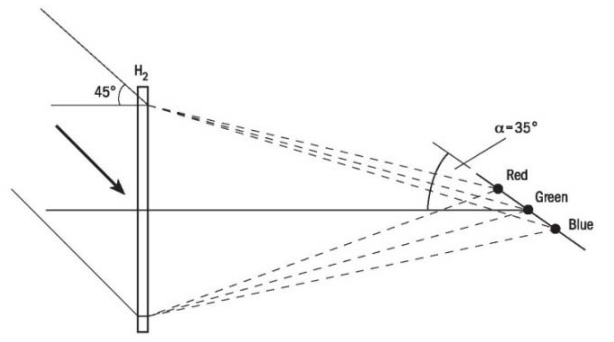


Fig. 4. For white-light replay the images of the slit are formed at different heights and distances from the H2 hologram, lying on a line at the achromatic angle to the horizontal

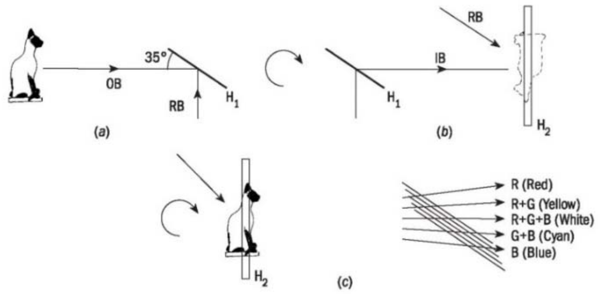


Fig. 5. The master hologram H_1 is made at the achromatic angle, for final reconstruction at 45° (a). The reference beam is shown as orthogonal to the object beam; The flipped master H_1 is used to make an image-plane transfer hologram H_2 (b); transfer hologram H_2 is flipped and illuminated by a white-light point source (c)

SLM pixel changes laser light intensity and objective directs modulated laser light towards photosensitive medium under different angles. The holographic optical element — hogel, recorded at the place of objective's waist, while illuminated will diffract light to the direction from where the laser light came to it during recording and with intensity defined by SLM pixel (Fig. 1).

2. Pixel swapping

Fig. 2 illustrates the principles of the pixel swap process which is described in details in [21]. From the sequence of digital parallax-related images all the pixels with the same coordinates are taken and a new composite image is combined from them. This image is projected on the SLM and a hogel with the same coordinates. For example, if we have an image sequence with image resolution of 640 × 480 pixels, we can print a hologram from it having 640 × 480 hogels too, i. e. if our hogel has a size of 0.1 mm, the resulting hologram will be 64 × 48 mm. The hogel with coordinates (0, 0) will contain all the pixels with coordinates (0, 0) from all images in sequence. The hogel with coordinates (0, 1) will contain pixels with coordinates (0, 1) and so on. And when observer will change his viewpoint in front of the hologram, he will perceive the pixel with coordinates (0, 1) as it was on the image of the 3D scene taken from this particular angle. Similarly, the hogel with coordinates (0, 2) will show him all the pixels with coordinates (0, 2), and so on. Thus the whole direct-write digital hologram viewed from different angles will show to observer the images of the 3D scene taken from different angles.

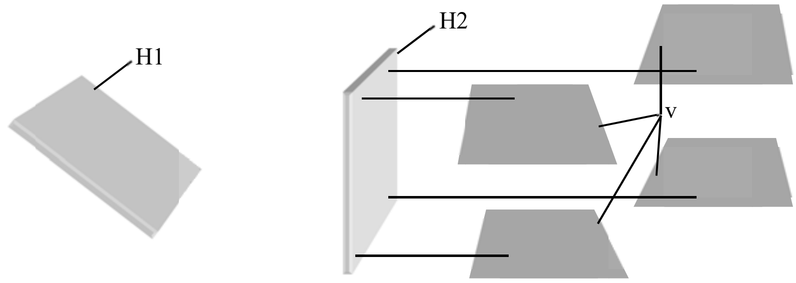
If the hogel has size 0.1 × 0.1 mm, the final resolution of the hologram will be 254 dpi, which seams lower than resolution of desktop photo printers which use for photographs at least 600 dpi, but that is not exactly true. Each hogel contains several hundred basic pixels. When we view the holographic print, our eyes and head perform involuntary movements, so we perceive several views at a time and our brain integrates them. Each adjoining parallax-related image contains only a small variation in the detail of the scene, so the difference is not perceptible, but our brain integrates and notes those details, which would be lost if this were a 2D print with 254 dpi. Thus a holographic print with 0.1 × 0.1 mm hogels will be observed as if it had a resolution of 700–1000 dpi.

3. Pixel swapping for achromatic hologram

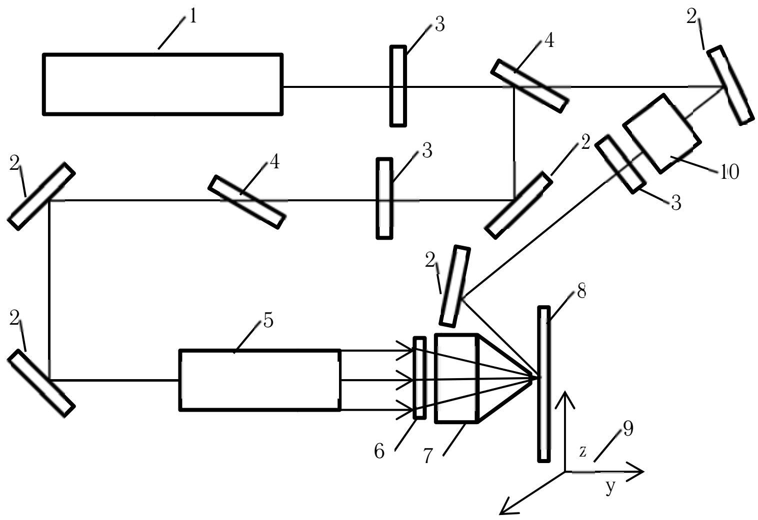
Surface relief holograms that can be used for mass-replication with existing hologram embossing equipment actually are White-light transmission (WLT) holograms. When those holograms are produced by classical analogue holography means, first the H1 master-hologram is produced, and then H1–H2 holographic image transfer is performed as it is shown on Fig. 3.

H1 master hologram for the Rainbow WLT hologram is just a narrow strip of 4 mm [22]. When H2 transfer hologram is lit by white light, the holographic image of it is viewed through the real image of the slit. And when observer moves his head vertically he is looking through the real image of the slit as formed by a different part of the spectrum, and as a result, he will see the image in a different color; in fact the whole spectrum is spread out along a sloping plane tilted to an angle called achromatic (Fig. 4) [23].

If the H1 master hologram is recorded while the photoplate is tilted at the same achromatic angle and during the transfer not the slit, but whole master hologram surface is used — the H2 transfer hologram will disperse the white light in such a way, that there will be a viewing zone



H1 — master hologram, H2 — transfer hologram, V — views of H1 master hologram
Fig. 6. Images of H1 master hologram as they would be seen from different places on H2 transfer hologram



1 — Laser, 2 — mirrors, 3 — waveplates, 4 — Thin film polarizers, 5 — Object beam shape formation optics, 6 — SLM, 7 — Fourier objective, 8 — Photoresist plate, 9 — Photoresist plate movement, 10 — reference beam shape formation optics
Fig. 7. Schematics of Direct-Write digital holographic printer

where all rainbow colours are mixed into white light. In this zone the holographic image will be seen as achromatic Black & White image (Fig. 5).

To achieve the same achromatic image effect in Direct Write digital holographic printing, images for SLM shall be prepared mimicking this method of producing the analogue achromatic WLT hologram. If we will take a rectangular H1 master hologram, will tilt it to achromatic angle and look at it from the place where during analogue H1—H2 transfer is positioned H2 photoplate — we will see not the rectangle but a trapezoid. Moreover, while looking from the different places of H2 photoplate position, said trapezoid will be not symmetrical (Fig. 6).

Since with Direct-Write technique H2 transfer WLT hologram is produced at once, employing the SLM as small part of H1 master hologram, the image shown on SLM for each hogel shall also have different shape. The image for each hogel for Direct-Write WLT achromatic hologram will have asymmetrical trapezoid shape and parameters of this trapezoid will depend on the WLT hologram size, its viewing distance and viewing angle, reference beam angle, wavelength of the laser and Fourier objective used in the hologram recording system.

4. Materials

The positive photoresist plates were specially manufactured for Geola by coating an analogue of Shipley photoresist onto glass plates in size of 250 × 200 mm or 300 × 200 mm. For the bigger sizes holograms it is important that photoresist would be coated uniformly, to assure that, the coating was performed by blade coating method. Also this coating method produces thicker photoresist layer, which makes it more sensitive for pulse laser radiation.

As photoresist developing agent we have used Microposit developer AZ303, diluted with deionized water in proportion 1:9. Developing time was 25—35 seconds. It is worth to note that photoresist plates are commonly developed with some KOH or NaOH solutions. However, those chemicals remain in the developed relief and the thin layer of them is transparent. As a result, the holographic image looks great on photoresist, but as soon one will deposit silver on such a relief — silver enters into reaction with developer’s remains and the resulting silver relief is much shallower than the photoresist relief. Since the surface relief fringes reconstructing deep holographic image have very fine structure — developer's remains covering this fine relief highly affect reconstructed holographic image quality. Most likely Microposit developer AZ303 has some proprietary surface active ingredients preventing developer’s remains layer formation and therefor is advisable to use when fine relief fringes are needed to be obtained [24].

Fig. 8. Projector and screen setup and images sent to LCD projector

a) b) c)

d) e)

Fig. 9. Photographs of achromatic hologram acting as projection screen. White road sign projected onto the achromatic hologram front views (a), (b) and side view (c). Colour image projected onto the achromatic hologram front view (c) and side view (d).

5. Equipment

For achromatic WLT holograms recording on photoresist we have used Geola's pilot Blue Phoenix series WLT holograms printer DIWO-6. Principal scheme of the printer is shown on the Fig. 7.

In DIWO-6 holographic printer is employed Geola's BlueBird series pulse laser (40 ns pulse duration, 440 nm emitting radiation wavelength, 30 Hz repetition rate, 1mJ pulse energy). Because of the pulse laser employment there is no need to stop photoplate for its stabilization before each hogel recording. The laser is flashing continuously, the photoresist plate is moving continuously and one hologram line is recorded. Then the photoresist plate is shifted for the distance of 0.1 mm (size of the hogel) and next hologram line is recorded. Before the hologram printing, the photoplate distance from objective is adjusted in such a way that object and reference beams would be overlapping at the photoresist layer. During the printing this distance is kept automatically by shifting the photoresist plate in y direction.

Hogels produced by this printer have size 0.1 × 0.1 mm. Maximum size of photoresist plate handled is 200 × 300 mm and the maximum hologram size is 152 × 152 mm (6″×6″). Printing speed is ≈ 7 minutes for one square centimeter and it takes only 25 hours to print this maximum size hologram which makes this printer the fastest one amongst master-originals Originators in embossed holography domain.

Pixel-swap process in this Originator is separated from hologram printing process. The sequence of parallax-related images is submitted to PC with Windows 7 operating system running proprietary Geola's software which performs pixel-swap and stores images for each hogel. Parallax-related images for the screen were 124 identical images of white rectangle in size of 1000 × 1500 pixels. Pixel-swap process took two minutes and then in 18 hours hologram of the screen in size of 100 × 150 mm was printed.

For the image projection on the printed screen hologram we have used LED projector LG HS 102.

6. Results

The exposed and processed photoplate with achromatic hologram of white screen was placed vertically in a universal plate holder. The video projector connected to the laptop was placed on a tripod in such a way that light from it would be coming to the hologram at an angle similar to the reference beam angle used in DIWO-6 originator for its recording. Images that were showed on a laptop screen were white image of a turn side on a black background and colour photograph of one of our poster-sized colour volume hologram printed on our other DWDH printer (Fig. 8).

On the Fig. 9 are shown photographs of the screen with projected image. Since the hologram acting as screen is achromatic — all projector's LED wavelengths are replayed correctly with right intensity and into the viewing angle defined by printers hardware and software.

As it is seen from photographs above, the achromatic hologram of white screen imprinted at the image plane indeed can act as see-through screen. And since it is surface relief hologram — it can be easily replicated and become a cheaper alternative to the photopolymer see-through screens.

Conclusions

– Achromatic surface relief hologram of the white screen was produced employing Direct-Write Digital Holographic printing technique.

– This hologram can be used as a master-hologram for the see-through screens manufactured with embossed holography methods.

– Producing the see-through screens employing embossed holography methods shall significantly reduce costs of their production.

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