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ADVANCED CONCEPT FOR CREATION OF SECURITY HOLOGRAMS

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A new concept is proposed for digital hologram production along with the relevant techniques developed in our laboratory. The main idea of the concept is to maximally separate the calculation of hologram from its optical recording on the light-sensitive media. A special file format containing information on each holographic pixel is created at the stage of calculation. The file is a device-independent by structure, and can be employed for recording a hologram using any of the existing techniques (dot-matrix, optical matrix lithography, e-beam lithography). An optical lithography device is applied to calculate the images for a spatial light modulator at the stage of hologram recording in accordance with the data from the file and in conformity with the hardware features of the device. The proposed method was tested and successfully used to record security holograms. For commercial use a software package and an optical recording system have been developed.

Keywords: *holographic recording, digital holography.*

1. INTRODUCTION

Nowadays, security holograms are used in most printing applications where additional protection level is necessary, e.g. credit cards, passports, bank-notes and any types of valuable documents. A common type of protective hologram is the so-called relief-phase hologram, which can easily be mass-produced at a low cost by the embossing technique. Holograms are to be applied to a document or a product, and the presence of a hologram is intended to reliably indicate that the document (product) is authentic.

To create a holographic image on a photoresist plate several technologies exist. They can be divided into three basic types: the analogue, i.e. holograms are produced by the classical methods of optical recording; the digital, where the holograms are produced by the ‘dot-matrix’ technology [1, 2], the interference optical lithography [2] (so-called 'image-matrix' technology) and the e-beam lithography with a high resolution power [3] (not often used); the third type of hologram recording is a combination of synthetic and analogue elements. The dot-matrix and image-matrix technologies of optical recording are now widely used for recording security holograms with the protection from a low level up to its highest level.

These technologies have become popular due to a reasonable price of equipment, the high quality of the holograms as well as the ease of operation and maintenance with minimum special knowledge required.

However, each holographic equipment manufacturer has its own concept and methods for calculation of the hologram structure, which are closely connected with the peculiarities of the recording device [4, 5].

In this paper, we propose and describe a new approach to the creation of security holograms. The main idea is to separate the stage of the hologram calculation process from the stage of optical recording. As shown below, this approach has many advantages over the traditional one.

2. THE CONCEPT

The general concept underlying the process of security hologram creation and the structure of a binary holographic file are shown schematically on Fig. 1.

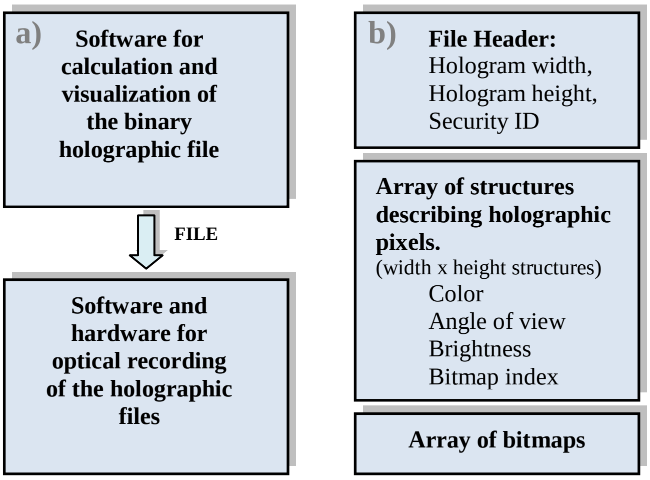

Fig.1. a) Common concept of hologram creation.
b) Structure of the binary holographic file.

In the first stage (Fig. 1*a*) a special type binary file is created using the developed software package. The file contains all the necessary information for the optical recording of a hologram. This is a device-independent file, because it does not contain any specific information about particular features of the recording device.

After one or more holographic files are established, they can be used for recording security holograms. The software of the optical lithography device downloads a selected number of files necessary for recording; and, after some additional settings relevant to a particular file, a consistent hologram recording is done for these files.

The structure of a holographic file is shown on Fig.1*b*. At the beginning of the file there is a header which contains information about the size of a hologram and the unique number (ID) that identifies the developer of the hologram. The maximum image size may be approximately 4200 Megapixels. The unique identifier is used to link files to a particular hologram recording device. Thus, the seller of equipment identifies each customer by its ID number. The buyer of the hologram recording device can create holographic files only with his ID number, and, accordingly, the lithography system can use files to record holograms only with a definite ID number. This approach is designed to prevent hologram counterfeiting on similar equipment from other manufacturers.

The header file is followed by an array of structures that describe the parameters of each holographic pixel. The main of them are:

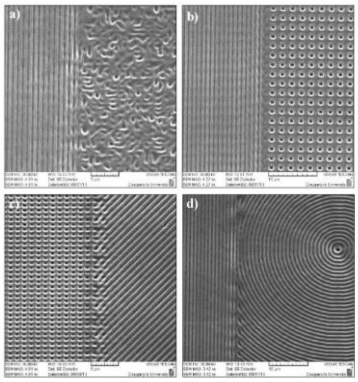

Fig.2. SEM images of the hologram surface where diffraction grating combines with functional microstructures: a) light scattering microstructure; b), c) 2D diffraction grating; d) axicon grating.

- Color of the pixel corresponding to the standard position of the hologram lighting source.
- Viewing angle at which the pixel becomes visible on the hologram.
- The brightness of the pixel relative to the maximum value.

A diffraction grating with definite period, orientation angle and depth of the relief is the main microstructure in security holograms. The structural parameters are used to calculate the image of the diffraction grating with the required parameters for each pixel of the hologram. A distinctive feature of the recording device created by us is the ability to use a variety of functional microstructures for the pixels of hologram. Examples of some microstructures in conjunction with a diffraction grating are shown on Fig.2, and their profile – on Fig.3. In order to record them, an array of images corresponding to such microstructures is provided in a holographic file.

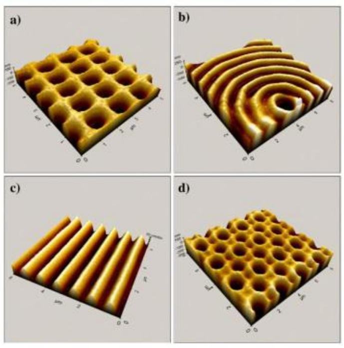

Fig.3. AFM images of hologram surface with microstructures:
a), d) 2D diffraction grating; b) axicon grating; c) diffraction grating.

If the pixel is not a diffraction grating, a corresponding structure in the file is assigned to the array index of the image bitmap. For our type of holographic file up to 10 different microstructures can be used. The use of functional microstructures significantly enhances the visual and protective features of the hologram.

In our opinion, the use of the concept of holographic files has a number of advantages. Some of them are as follows.

The file contains all visual information about the hologram. This means that at any stage of development of the hologram the visualization software allows generating a color image of the entire hologram or of a selected part (Fig. 4*a)* for a particular angle of observation or for all angles at once. It is possible to generate bitmap files for the distribution of orientation angles or for brightness of pixels as well as for extraction of bitmap image array from the file. The ability to calculate the hologram images for different viewing angles allows for a hologram's animation. This is convenient both for the graphic design process and for the presentation to potential customers.

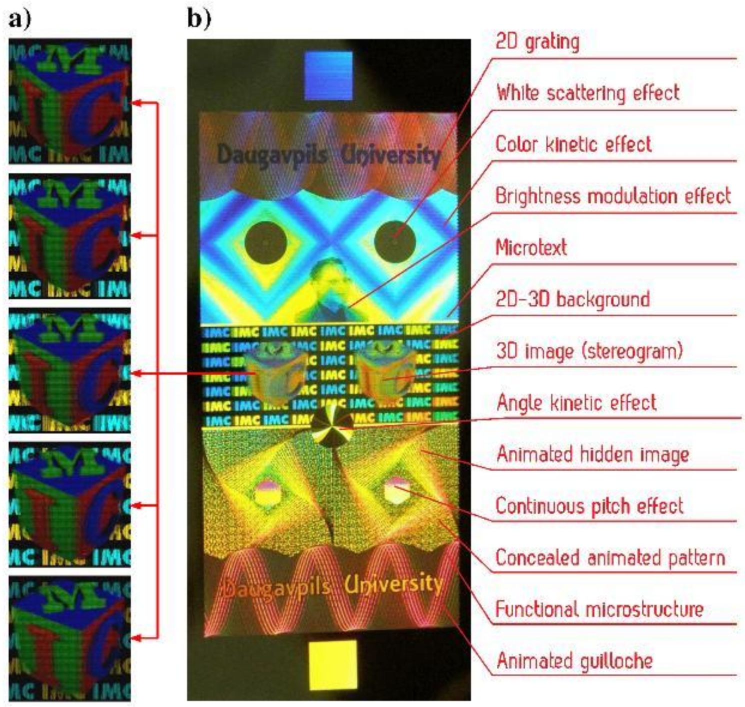

Fig.4. a) Visualization at different angles of the part of hologram with stereogram.
b) Photo of the security hologram with some of the visual effects.

One of the strong points of the proposed concept is the possibility of mathematical operations on the files and the internal data structures. For example, a direct addition of differently sized files (with or without a mask) is possible. In the meantime, the image of a single file is added to or combined with an image of another file. A pattern of the hologram obtained by combining a large file with multiple same source files is shown on Fig.5*b*.

The subtraction operation allows cutting or copying a part of the holographic image file to a new file. It is possible to increase the image file to an integer number of times that would allow combining in one hologram the images with differing graphic resolutions. Also unary operations could be applied to files; for example, we have developed procedures for changing the intensity and orientation angles of certain pixels (so-called brightness and angle modulation effects) or a more complex emboss effect in which the holographic image creates the illusion of three-dimensionality of a convex or a concave surface. Another interesting possibility is the creation of a library of files for different visual effects. By grouping and combining files with different effects, complex security holograms can be created in a short time, sometimes even bypassing the stage of design work. A pattern of the security hologram with different visual effects is shown on Fig.4*b*. The hologram was created by adding multiple files without preparing a sketch in the graphic software. Figure 4*a* demonstrates visualization of the area of a hologram for multiple viewing angles. It is worth mentioning that the mathematical manipulation with holographic files and their calculation based on the graphic design is not time-consuming. For instance, the 4300x8500 pixel hologram corresponds to a holographic image file size of 110Mb, and any adjustment operations with such a file take 2-3 s on a computer with i7-2600 CPU 3.4Ghz processor.

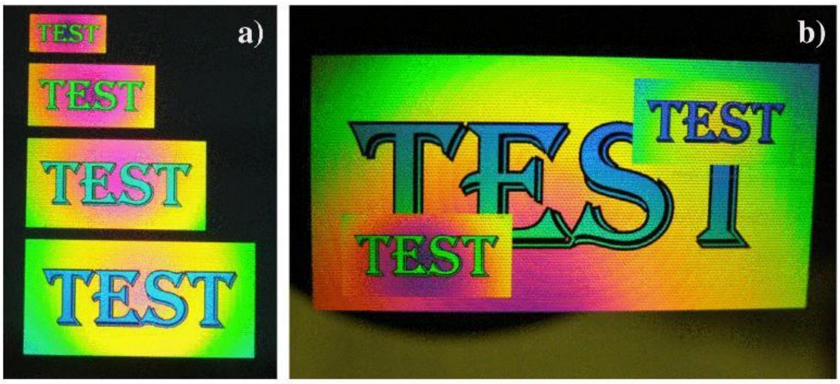

Fig.5. a) Holograms of different size recorded from the same file.
b) Hologram created by combining mathematically the same files with scaling.

A software package developed by us for creation of holographic files and diversified operations on them has been successfully used to record security holograms at our research centre. We also offer our developments for commercial use [6].

3. RECORDING SECURITY HOLOGRAMS

Several devices have been developed and assembled to record security holograms. One of the devices intended for commercial use is shown on Fig.6. More information about the operating principles of the offered equipment can be found in [2, 7-9].

Fig.6. View of the device created for security hologram recording.

The possibilities of the optical lithographic recording device in the context of holographic file application are as follows. The software of the device downloads the selected file into the memory. Next, it calculates a graphic image for the spatial light modulator (SLM) before each exposure based on the internal structures of a file. The basic parameters are set for each file before recording: the positioning coordinates (x, y) of the hologram on the plate, the sizes of the hologram (width, height) and the exposure time. The sizes can be set arbitrarily by user (for holograms of different size recorded based on the same image file see Fig.5*a*). At changing the size of a hologram only the size of holographic pixels is changing, while the number of pixels remains the same. The minimum increment size of the hologram depends on the file size and the number of parameters of the recording device, varying in the range of 0.05-0.5mm.

The controlling software of the recording device has additional settings that affect the calculation of holograms and their visual characteristics.

Since the diffraction angle of the pixels has a limited scope, for large holograms a color distortion of the pixels that are remote from the center of a hologram is tangible. For this case, the option of correcting the pixel colors (so-called lens effect) is provided.

The light source positioning parameter for hologram observation can be set in the range 30-40^o. The color contrast of the hologram increases with the angle; however, the applicable frequency range of diffraction gratings also increases (at α=30^0 f=730-1160 mm^{-1}, and at α=40^0 f=940-1500 mm^{-1}), which leads to a slight decrease in the diffraction efficiency (DE).

It is possible to select the mode of changing the brightness of pixels during the hologram recording. The first mode changes the relative size of the pixels, while the DE remains the same. In the second mode, the size of all pixels is identical, with only their DE changing, which is achieved by varying the depth of a diffraction grating relief. Size modulation has a good linearity, but gives better results only for large pixels (> 35 μm).

The data structure of the holographic file describes the parameters of the microscopic parts of a hologram – the diffraction pixels. At recording a security hologram by ‘image-matrix’ technology one frame is recorded in a single exposure, depending on the graphic resolution (with the number of diffraction pixels from ten to tens of thousands). The computer calculation of images for SLM is done before each exposure; therefore, it is necessary to know the speed of the hologram recording system based on its graphic resolution.

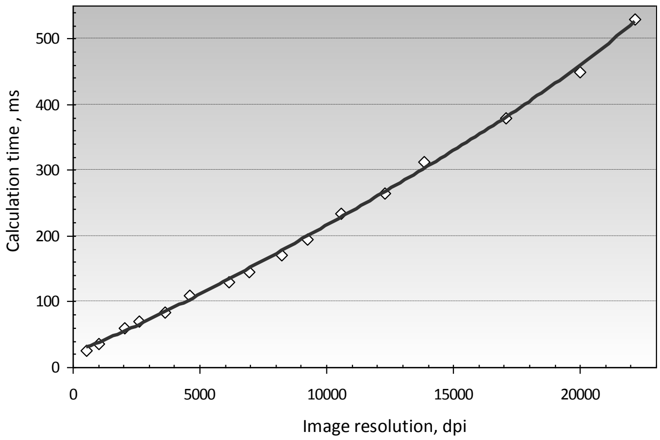

Fig.7. The time of frame image calculation for 1920x1080 SLM depending on the resolution of a hologram (i7 CPU 3.4GHz).

The image calculation speed for SLM depending on the graphic resolution (the number of diffraction pixels per inch on hologram) is experimentally determined and shown on the graph of Fig.7. During each exposure cycle of the hologram section, simultaneous calculation of the image and positioning of the system in the new area for the record are performed. For precise positioning of the plate with photoresist and pausing to eliminate mechanical vibrations the time of ~ 170ms is required. The image frame with a resolution of ~ 7000dpi can be calculated during mechanical motion (see Fig.7). The hologram recording speed can reach up to 4 exposures per second, taking into consideration the exposure time of ~ 80ms. The result of ~4cm^2/h can be achieved if the size of the frame on photoresist is 225x115um. If the resolution is >7000dpi, more time is required to calculate the image frame than is spent on the positioning of the recording system. If the graphical resolution is 20000dpi, the total time of optical recording cycle is 600 ms, which corresponds to the hologram recording speed of ~1.5 cm^2/h.

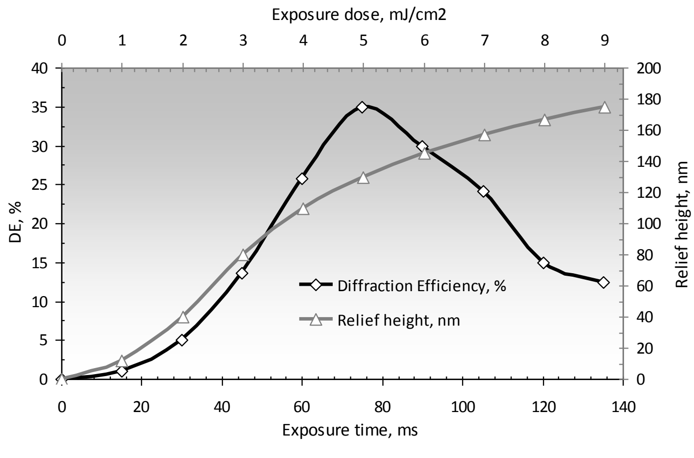

Fig.8. Diffraction efficiency (DE=100*I_{+1}/I_0) and relief height *vs.* exposure dose for photoresist AZ1514, 1.5um coated after development with a 30nm Ag layer.

The most important quality parameter of the relief-phase holograms is their visual brightness, which is analytically determined by the diffraction efficiency (DE) of diffraction gratings compounding a hologram. In the hologram manufacturing process, DE depends on many factors: most important of them being the exposure of optical recording as well as the concentration of the developer and time of developing the photoresist. The DE and the diffraction grating surface relief (F = 1100 mm^{-1}) dependence on the exposure under the same developing conditions is shown on Fig.8. When recording security holograms on the equipment of our own engineering, we have obtained consistently high results for DE (normally found in the range 26-33%). For comparison, the average DE result for the good-quality holograms produced by other manufacturers is found to be 22-28%. An exception is the holograms with asymmetrical profile of the diffraction grating which are produced by the electron-beam lithography or the photo-lithography. The DE of such holograms can reach up to 42%; however, these techniques are very expensive, and have limitation as to the use of some specific visual effects.

It is necessary to perform precise focusing of the optical scheme during the adjustment stage to achieve a high-quality hologram recording. We have developed a semi-automatic high-accuracy focusing system. The focusing lens is moved obeying the commands of the optical system operator with a micron accuracy using a stepper motor. During the focusing stage, special graphic image is displayed on the SLM, and the light reflected from the surface of photoresist forms an image on a matrix of CCD camera. The operator gains the maximum clarity of focused image on the CCD camera using the control program (Fig.9). This method allows achieving a high-accuracy local focusing, because the operator can see the quality of interference for the test image on the display. The modes of focus adjustment for the hologram recording are:

- A single focusing anywhere on the photoresist: the result of focusing is used for recording all holograms.
- Focusing near each hologram: inherent focusing result is used for each hologram recording. This focusing mode is useful for recording an array of holograms or for optical recombination.
- Focusing at three spaced points on the photoresist: intermediate focusing values are calculated during hologram recording. The method is mainly used for large holograms.

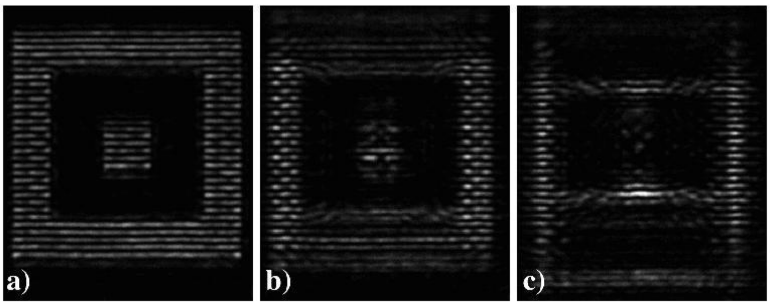

Fig.9. Images from CCD camera registering the focusing state of recording system: a) in focus; b) 10 um out of focus; c) 20 um out of focus.

4. CONCLUSIONS

The new concept of security hologram creation has successfully been tested under laboratory and industrial conditions, and is shown to be suitable for recording high-quality holograms of the type.

In compliance with the concept, a special file has been designed that fully describes the holographic structure. The proposed method supports both standard designs using graphic software packages (CorelDraw, Photoshop and etc.) and mathematical modelling of different visual effects. Visualization and animation of the image of a security hologram stored in the file are possible at any stage during the design development. The use of holographic files enables realization of optical recording of diversified holograms with individual settings (size, exposure, location, etc.) in a single recording cycle.

Since the calculation of a holographic file's structure and its optical recording are carried out with the help of the computer software and the equipment of our own design, some of the considered methods are unique and are not encountered in digital holograms.

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PROGRESĪVĀ KONCEPCIJA AIZSARDZĪBAS HOLOGRAMMAS IZVEIDEI

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K o p s a v i l k u m s

Šajā rakstā tiek apskatītas koncepcijas un metodes, kuras tiek izmantotas drošības hologrammu ražošanai mūsu laboratorijā. Koncepcijas galvenā ideja ir hologrammas aprēķina posmu maksimālais sadalījums no hologrammu optiskā ieraksta uz gaismas jūtīgām vidēm. Hologrammas aprēķina posmā tiek izveidots īpaša formāta fails, kas satur pilnu informāciju par katru hologrāfisko pikseli. Pēc struktūras fails ir neatkarīgs no ierīces un to var izmantot hologrammas ierakstam pēc jebkuras no esošajām tehnoloģijām. Hologrammas ieraksta posmā optiskā litogrāfijas iekārta pēc faila datiem veic SLM (Spatial Light Modulator) attēla aprēķinu, ievērojot iekārtas darbības īpatnības. Piedāvātā metode ir pārbaudīta un veiksmīgi tiek izmantota drošības hologrammu ierakstam. Izstrādāta programmu pakete un optiskā ieraksta iekārta komerciālai izmantošanai.

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