Fabrication of digital rainbow holograms and 3-D imaging using SEM based e-beam lithography

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Abstract: Here we present an approach for creating full-color digital rainbow holograms based on mixing three basic colors. Much like in a color TV with three luminescent points per single screen pixel, each color pixel of initial image is presented by three (R, G, B) distinct diffractive gratings in a hologram structure. Change of either duty cycle or area of the gratings are used to provide proper R, G, B intensities. Special algorithms allow one to design rather complicated 3D images (that might even be replacing each other with hologram rotation). The software developed ("RainBow") provides stability of colorization of rotated image by means of equalizing of angular blur from gratings responsible for R, G, B basic colors. The approach based on R, G, B color synthesis allows one to fabricate gray-tone rainbow hologram containing white color what is hardly possible in traditional dot-matrix technology. Budgetary electron beam lithography based on SEM column was used to fabricate practical examples of digital rainbow hologram. The results of fabrication of large rainbow holograms from design to imprinting are presented. Advantages of the EBL in comparison to traditional optical (dot-matrix) technology is considered.

OCIS codes: (090.5640) Rainbow holography; (110.4235) Nanolithography; (060.4785) Optical security and encryption; (220.4241) Nanostructure fabrication; (160.5470) Polymers.

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1. Introduction

Power of digital holography is defined by numerous applications and methods. One of the recent directions of digital holography is a method dealing with a real (3D) color object that is observed in several projections and the projections are then recorded with a photo-sensors matrix. Numeric methods are used to recover the object as 3D (color) virtual object in a computer. The computer screen is used for observation of the object [1–3]. The method is used to recover small (up to micron range) or remote objects (see recent examples [4, 5]). Another application branch of digital holography (the one we present in this paper) is operating in the “opposite direction”. At the beginning a virtual 3D color object is created in a computer. Several “projections” of the 3D object are acquired and saved in computer memory. Then the data of these “projections” is used to modify a layer of material in such manner that an observer is able to see the written 3D object after illuminating it with light. Different technologies are used for surface modification but most popular are photolithography and electron-beam lithography. These technologies were exploited for fabrication of various synthetic holograms (or diffractive optical elements, DOE) not only for the simple binary amplitude or binary phase holograms but including so-called kinoform DOE. Rather early electron beam lithography was suggested [6] and used for fabrication of (kinoform) DOE [7]. Digital holography methods were used for fabrication of the first X-ray hologram by means of electron beam lithography where thin Ni “islands” were used as phase-shifting layers [8]. More practical X-ray focusing elements (DOE-lenses) were fabricated using the similar digital design and fabrication tools [9, 10].

Optical grating structures enable a controlled manipulation of visible light by interference effects occurring in evenly spaced nanostructures. Sets of diffractive gratings generate rainbow “holograms” which are used as security features [11] for the protection of products and official documents (passports, ID cards, etc.). It was recognized rather early that e-beam lithography could produce structures of highest quality (e.g [12–16]). Flexibility in shape of elemental gratings as additional security in comparison to optical dot-matrix technique was pointed out in [16, 17]. However, the fabrication of appropriate structures in the submicron and nanometer range is technically very demanding and requires complicated and costly equipment. The main challenge is a large area of the “hologram” which is comparable with

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products of semiconductor industry. Therefore usually industrial e-beam lithographs are used for stamp fabrication [18], which leads to fairly high costs for these holographic components. All the above facts increase the cost of a final product.

This article is devoted to the description and substantiation of a technology based on an electron-beam lithography with the use of such a cheap device, as the column of scanning electron microscopes. The technology allows an essential reduction of the cost of stamps for rainbow “holograms”. The discussion explains why the quality of a rainbow “hologram” nevertheless remains high. The basic formulas used at designing rainbow “holograms” are submitted. The color synthesis in this case appears to be distinct from color synthesis in a dot-matrix technology [19, 20].

The fabrication of suitable nanoimprint stamps made of nickel with feature sizes down to 100 nm is also described.

2. Physics and optics of rainbow holograms

The reflection of white light from a diffraction grating is known to result in light decomposition, to give a rainbow. This means that a viewer would see the site of a white light reflection in color at a certain positioning of a light source and a diffraction grating. A slight displacement of the viewer eye or slight swinging would cause changes in the color of the reflection site. The color observed depends on the angle of white light incidence, observation angle and diffraction grating period. Varying the grating period, a reflection can be obtained such that a viewer would simultaneously see three different sites of different colors. These properties make the basis of rainbow holograms. The surface of a sample is filled with diffraction gratings of various periods so that a full-color image could be seen at a proper positioning of a viewer with respect to a light source. A general disadvantage of creation of a colored image with diffraction gratings is that the color of a product changes upon its swinging. Although a grating pack is not a real hologram, these products are commonly called rainbow holograms. Other terms occasionally used are grating-pixel holograms or iridescent holograms OVDs [21].

2.1 Gratings size and image stability

As to practical usage of a rainbow “hologram”, it should be noted that the rainbow angular size at reflection could be made so small that a viewer would see the reflected light only with one eye. So, other gratings sets can be drawn in such a way that would send color light to the other eye of the viewer. This means that two different images can be created, each seen with one eye alone. It follows that a stereo effect, an illusion of observing a three-dimensional image, can be created. One more important thing is to be mentioned. It turns out that diffraction gratings even if they do not consistently fill the surface, can form a fairly bright image. Filling of the surface by 5% gives an excellent brightness when viewed in the sunlight. So, for example, ten stereoscopic pairs of images reflecting at different angles can be drawn and a viewer could see all the ten (stereoscopic) images by simply swinging the rainbow hologram. So the illusion of observing a moving 3D colored image can be created by forming diffraction gratings properly arranged on the sample surface.

The number of images drawn depends on the size of a diffraction grating: the smaller the size, the greater number of images can be drawn. Naturally, there exists a limitation to the minimum size of a grating; if the size is small the amount of reflected light is small too and the image brightness is low. Therefore, the minimum grating size and the maximum number of images drawn are also determined by the illumination brightness. There is one more condition limiting the grating size d. Light diffraction on a square pixel (square grating) of d size at reflection causes an angular divergence (blurring) by the order of magnitude λ/d in both directions (λ is a wavelength). Therefore, a too small size of a grating can give rise to a situation where diffractive divergence is high and reflected rays would fall on both eyes, which means that the creation of a stereoscopic effect is impossible for a small grating size d. One more point to be mentioned here concerns the optimum size of a diffraction grating. The grating size seems of no special importance because diffraction angles are determined by a grating period. However, the stability of colored image observation is essential for a viewer (for example, upon swinging in different directions or slight vibration). Therefore, the above angular divergence (blurring) could be of use because swinging at angles smaller than diffraction blurring λ/d would not cause the disappearance of an image or appreciable changes in the color. So, a reduction of a grating size would make the image observation more stable, and the stability is the higher, the greater the angular blurring.

The above consideration leads to the conclusion that an optimum grating size d is determined by a set of conditions. The package “RainBow” [22, 23] opens up possibilities for a user to make an optimum design. The second part of the package permits in situ simulation of the above factors to predict an image before a real hologram fabrication what makes hologram optimization quicker and cheaper.

2.2 Color formatting (synthesis)

Color synthesis in a rainbow hologram is usually based on the so called RGB color model [24]. The model requires the provision of definite intensities of R, G, B components. Several ways are known to control the intensity of color light reflection by diffraction gratings. One is to control the intensity via the grating size, the larger the grating area, the more light it would reflect towards a viewer. Another means is to change the height of the diffraction grating relief; if the relief height is smaller than optimum, the image would be dim and pale. One more way of changing the reflection efficiency is to change a grating duty cycle. An optimum duty cycle is 50% (step width is equal to the half period); by reducing the duty cycle (decreasing the step width without changing the grating period) one can change the intensity.

The formula relating the intensity I of diffracted light (in the first order of diffraction) with a duty cycle (h/d) of the grating is

$$\frac{I}{I_0}=\frac{1}{2}\left[1-\cos(\frac{2\pi h}{d})\right].$$

where h is a grating step width. It is seen that maximum diffraction is achieved at h equal to the half of period d.

Each of the methods has its own disadvantages. Realization of the duty cycle method gives structures (“ridges”) with a high aspect ratio that could be unstable at mechanical printing. Changes in the grating size result in a large change of the divergence angle resulting to color distortion at swinging. Variation of the relief modulation is difficult to realize in practice because of low tolerance of the development process to variations of a dose, time and temperature of development. The method is unpractical for a resist of high contrast.

The two first approaches seem preferable owing to the technological aspects of hologram fabrication and “RainBow” provides a possibility to choose and apply any of the two or even to exploit them simultaneously.

Note that the dot-matrix technique does not allow changes of the duty cycle.

2.3 Controllable blurring for color stability

Due to diffraction the elementary grating restricted by the α_x and α_y sizes has a natural angular blurring γ_x, γ_y which, with good accuracy, can be calculated as

$$\gamma_x \cong 2\frac{\lambda}{a_x};\ \gamma_y \cong 2\frac{\lambda}{a_y}.$$

This blurring is of fundamental character and cannot be reduced by any of available methods. The formula shows that blurring depends on the wavelength and can considerably differ in value. This means that red pixels on hologram rotation become extinguished later than blue pixels, which makes the colors of the picture distorted. The “RainBow” package helps to avoid this effect through equalizing angular blurrings for different wavelengths via the possibility to set an additional (although controllable) blurring. The procedure is as follows: a user defines a desirable angular blurring γ_0, then the software compares the blurring with an irreducible value and adds a controllable part of blurring. Outwardly, it looks like a slight distortion of the diffraction grating shape when straight grating strips are changed with arcs (Figs. 4, 6 and 9).

The dot-matrix technology does not allow producing such patterns and therefore direct writing with electron lithography has definite advantages in the production of hologram with stable color image.

2.4 Gray-scale hologram

Higher color stability at swinging can be illustrated with an example of gray tone hologram. With the dot-matrix technology, a gray-tone pixel of designed image is represented with 3 gratings of an (approximately) equal size. The lower the intensity of the gray pixel, the smaller are the corresponding sizes of the three gratings. As was mentioned above a smaller gratings have larger diffractive angle divergence (blur). This means that at swinging larger gratings become less visible and on the contrary smaller gratings preserve visibility. As a whole the intensity of a gray-tone picture would be distorted at swinging. Moreover blue color has a tendency to extinction and the swinging would result in the coloration of a primordial gray-tone image. The tolerance of a gray-ton hologram to swinging can be reinforced by adding a controllable blur. The tolerance of a gray-tone hologram to swinging is a good feature allowing a hologram fabricated with electron lithography to be discerned from the hologram produced by the dot-matrix technique. So the controllable blur provides an additional degree of security for a rainbow hologram.

3. Usage of conventional SEM columns as lithographs

The expenses of rainbow hologram production can be radically reduced if scanning electron microscopes (SEM) columns are used instead of industrial lithographs. An up-to-date SEM costs 150 to 300 thousand Euros, which is 10 to 30 times less than an industrial lithograph [18]. Generally the speed of drawing with SEM is slower than with industrial lithographs but for certain products, e.g. for rainbow holograms, the speed does not differ much and a rainbow hologram with an area of a square inch can be created within 6 to 8 hours.

The transformation of a SEM columns into a lithograph requires special hard- and software systems, e.g. NanoMarker [23]. Another important component is a special editor to transform color images presented e.g. in the **.bmp* format into properly arranged diffraction gratings and to present the data in a format convenient for electron lithography. The software mentioned (“RainBow”) provides an additional possibility of modeling image observation. This function is of importance in the step of designing because simulation of image formation helps to determine the arrangement of diffraction gratings prior to fabrication and testing of rainbow holograms.

The comparison with an SEM based lithograph with a machine of variable beam shape shows that due to non-parallelism of the gratings (see Fig. 4 and Fig. 6) the main advantage of the machines (writing with narrow but long strip) cannot be realized, so the system based on SEM has similar throughput at much more attractive cost.

4. Design of rainbow holograms

Let consider some examples of designing a hologram and data preparation for electron lithography. Figure 1 shows four color images in the BMP format. Each color image consists of three monochromatic images corresponding to three basic colors red (R), green (G), and blue (B).

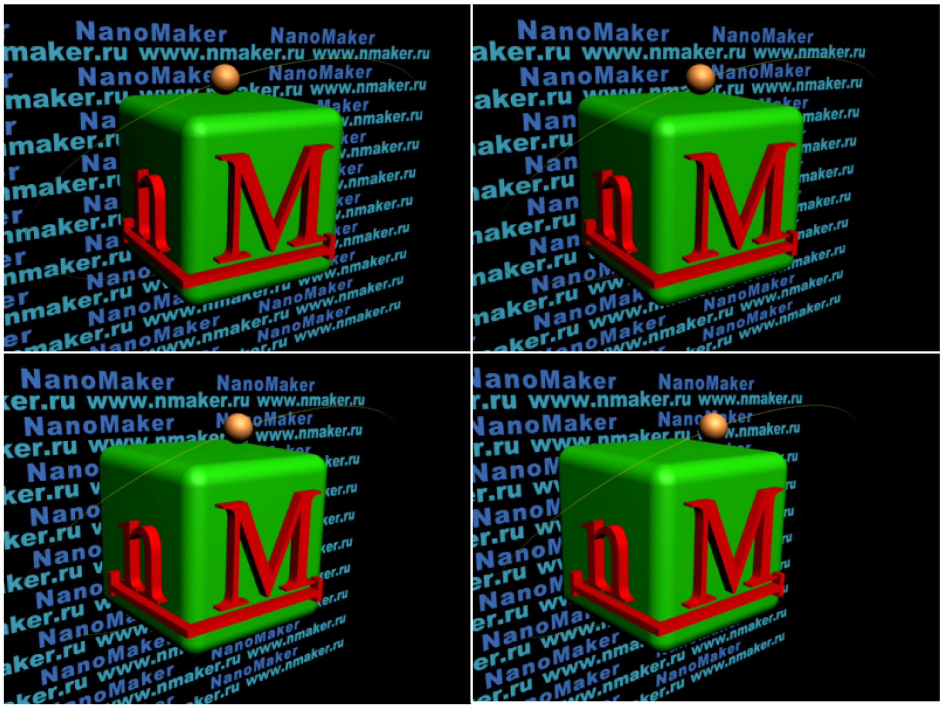

Fig. 1. Four (from five in total) images of a three-dimensional scene taken at various camera-angles, the angles differing by 5deg.

The brightness of each pixel corresponds to the color intensity of this pixel. A magnified fragment of an image (yellow ball) decomposed into three color components with the basic colors intensities presented in the scale of gray is shown in Fig. 2. It is seen that yellow-color consists of fairly intense R, G, and B pixels.

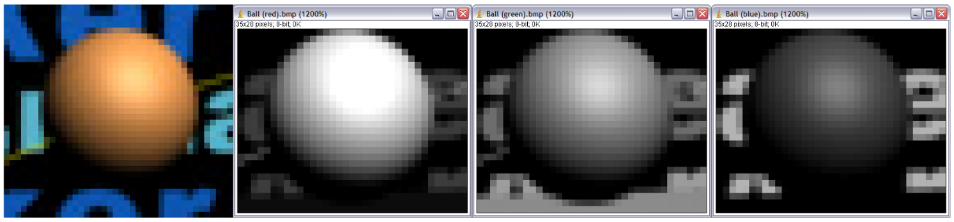

Fig. 2. Splitting of the initial color image into three (monochromatic) standard R, G, B images (the image corresponds to yellow ball in the initial image).

On the other hand, the bluish background is produced by a high intensity of B and G pixels only. The extraction of the three monochromatic components is the first step in the “RainBow” software. The next step is to determine the period of diffraction gratings on the basis of a pre-set geometry of illumination and observation. This step also includes consideration of R, G and B intensities via the calculation of a duty cycle or gratings area. Special attention is devoted to equalizing the divergence angle for all R, G and B gratings along the whole image.

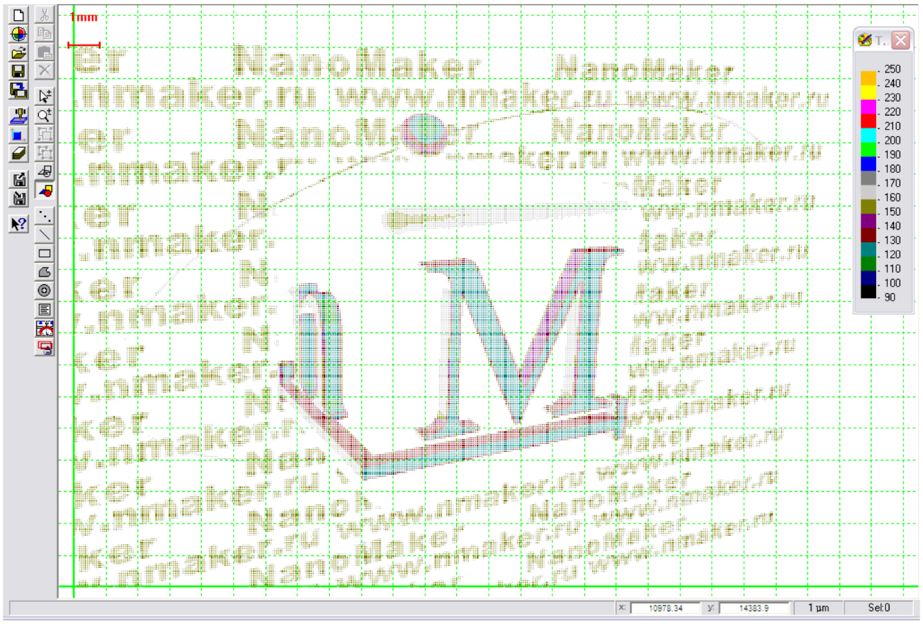

Fig. 3. Graphic presentation of the data for drawing gratings of "red" color (therefore all the gratings are of the same period).

The software "RainBow" allows the determination of three different wavelengths to calculate periods of diffractive gratings. By default, these three wavelengths are equal to 620nm, 540nm and 470nm for R, G and B components of a color image.

Then, a special procedure of proximity effect correction is applied which is always used when electron lithography is employed in microelectronics. The procedure is very important because it ensures an exact control over a pre-set pitch and a duty cycle and, hence, exactly conveys color intensities and the resulting color of a final image. Figure 3 shows a layer corresponding to the "red" color of one of the images in Fig. 1. Because of the proximity effect, gratings of different duty cycles or pitches must be exposed with various exposure doses (with different exposure times). Different doses are coded with different colors in Fig. 4 (see the vertical table). Also shown are several gratings and two separate gratings corresponding to different duty cycles. The low intensity pixel (Fig. 3, low-left) should be exposed with higher dose (gray color corresponds to the dose about 170%) than pixels of a high duty cycle (brown color corresponds to the dose 130%).

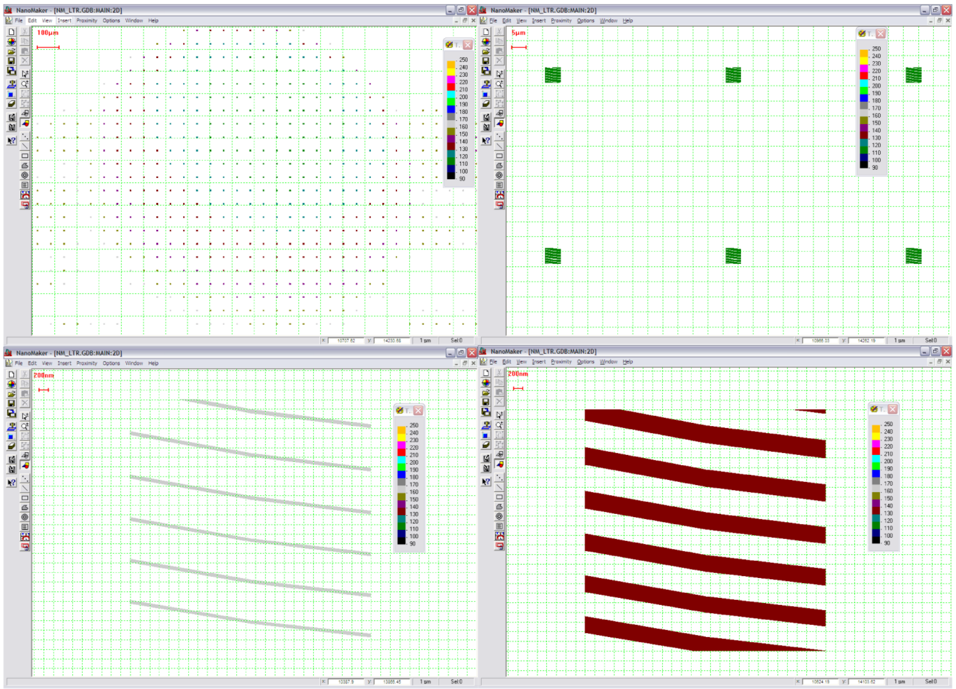

Fig. 4. Fragment of the data from Fig. 3 approximately corresponding to the yellow ball area in Fig. 2. Also shown are several gratings and two individual gratings of various duty cycles. Due to the proximity effect the grating with a low duty cycle (shown in gray color, low-left) should be exposed with a higher dose, brown color of the low-right grating corresponds to a lower dose due to automatic proximity correction procedure applied.

The creation of all the five color images requires 15 layers, three (R G B) layers for each of the five color images. All these gratings are shown in Figs. 5 (the area of the ball) and 6 (individual pixel). In this session of designing, an elementary diffraction grating size is 5 microns and the distance between the grating elements in one layer is 60 microns. These 60 microns is the resolution (size of the individual pixel) with which all the five images are created on the substrate by electron lithography. It is seen that the filling with the gratings for all the five images is about 20%, so there is room left for 15 more images.

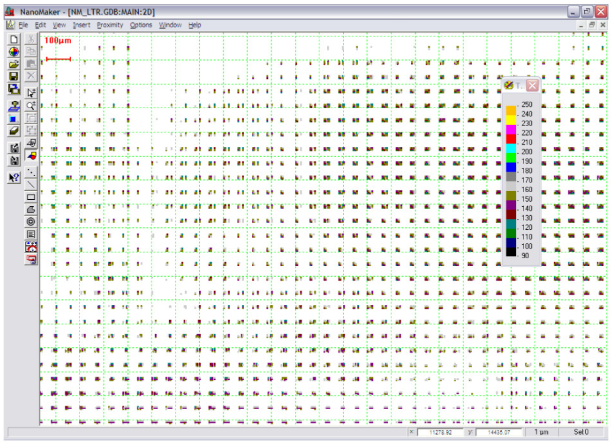

Fig. 5. Graphic presentation of lithographic data for the creation of all the five color images (Fig. 1) in the area of the ball. All 15 elementary gratings fill less than 20% of the available area.

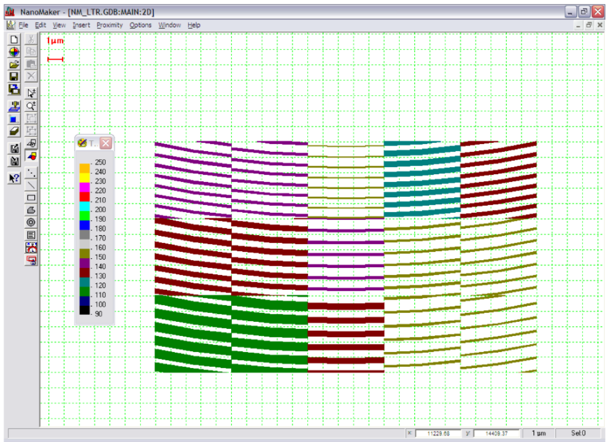

Fig. 6. Each vertical set of three gratings determines the color of an individual pixel and corresponds to one of the five initial images.

Simple estimation of the amount of lithographic data necessary for the description of any rainbow hologram gives values close to gigabytes when a conventional vector format like GDSII is used. This makes the operation with data and transferring the data difficult. To overcome the difficulty, a special (squeezed) format for rainbow lithographical data was developed drastically decreased the information amount by many hundred times. This highly reduced presentation is especially convenient at simulation.

5. Fabrication and testing

After exposure and development, nickel stamps are easily fabricated by electroplating (Fig. 7) and do not need any etching technique which is mandatory for silicon or quartz stamps.

Fig. 7. Photos showing two examples of rainbow holograms resulting from diffraction effects in nanoscaled grating structures, which are produced in a thin resist layer using e-beam lithography. At a certain angle a colored 3D image (right) and a flower (left) are visible.

The fabrication process used for metallic nanoimprint stamps is as follows: an optical grating structure with features sizes in the submicron and nanometer levels are generated in a 400 nm thin resist layer (2.2M polymethylmethacrylate, PMMA) using 30 keV e-beam lithography performed with a LEO1560 electron microscope equipped with a NanoMaker pattern generator from Interface company (Moscow).

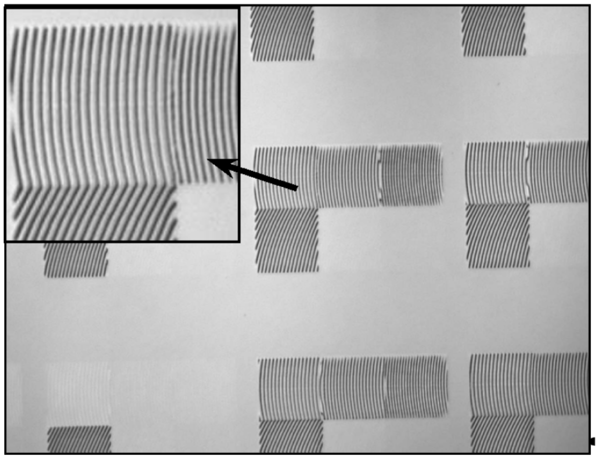

Fig. 8. Optical microscope image of the grating structures in a 400 nm thin PMMA layer fabricated with e-beam lithography.

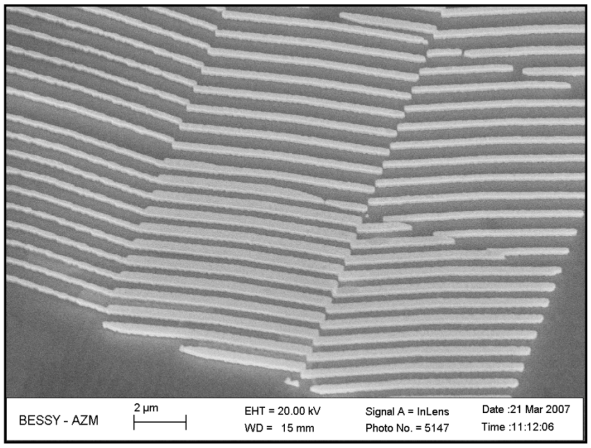

Fig. 9. SEM micrograph of the electroplated nickel stamp. The grating structure shows features in the submicron and nanometer ranges.

Figure 8 presents an optical microscope image and shows typical grating structures in PMMA. The structured polymer surface is then covered with a conductive nickel layer by thermal vapor deposition that serves as a starting layer for nickel electroplating. In this way, the topology of the resist is copied into a nickel structure as shown in Fig. 9. Detailed SEM analyses showed that features down to 100 nm are transferred during the electroplating step under optimized process conditions (see Fig. 10). The backside layer of the nickel stamp can vary in thickness between several tenths of micrometers to a few millimetres by adjusting the deposition time during the electroplating step. In an alternative fabrication method, iron is used instead of nickel.

Fabricated nickel nanoimprint stamps are imprinted into a PMMA substrate with a hot embossing machine HEX03 (Jenoptik Mikrotechnik GmbH, Germany).

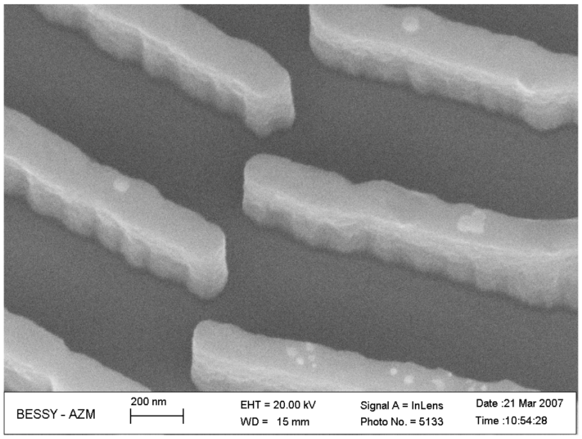

Fig. 10. Detailed view of the electroplated nickel nanostructures (300 nm high and approx. 150 nm wide).

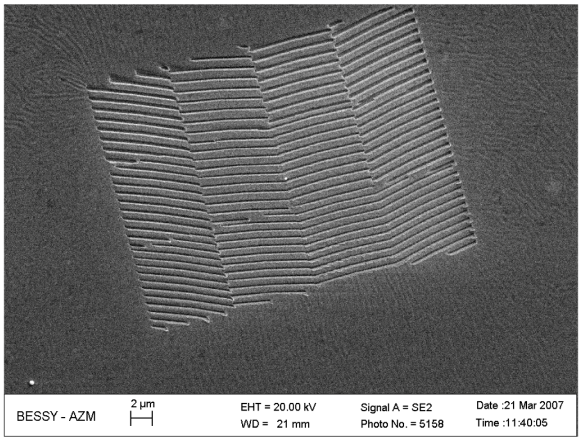

Fig. 11. The SEM micrograph shows micro- and nanometer scaled grating structures successfully imprinted into PMMA

Figure 11 demonstrates a successful pattern transfer of a nanometer scaled grid structure into the polymer.

5.1 Gray-tone example

To demonstrate the new features incorporated in the described approach, consider the results of fabrication of a gray-tone rainbow hologram. First a scene of observation was defined (Fig. 12) at the design stage. Supposing an incidence angle (Beta) equal to 45 degrees, the observation angle (Alpha) is then −7 degree. Angular divergences (blur) were chosen equal to 7 degrees in both directions. Elementary gratings were chosen equal in X and Y axes and were set to 22.5um. Such grating sizes result in irreducible angular divergence of ~1.6 degrees for a red wave and to ~1.2 degrees for a blue wave. It is seen that there is some gap between natural (irreducible) blur and predefined values. To achieve predefined value (for example, the above mentioned 7 degrees) and make the blur independent of the wavelength, the shape of individual gratings is slightly distorted causing an additional controllable blur produced by each grating. The result of the automatic procedure implemented in the "RainBow" design system can be seen in Figs. 6 and 8 where grating strips are not straight anymore.

The squeezed designed data were transferred to BESSY/AZM where the data were unpacked by the implemented NanoMaker standard tools.

Electron beam lithography was very similar to the procedure described earlier.

As a result, a perfect gray-tone hologram was fabricated as expected from simulation (please see [22] for example). A gray-tone image could be observed at changing angles of observation and incidence in the range ± 8 degrees with slight change in coloration.

A specially performed simulation confirms the observation of gray-tone preserving. The simulation also showed that the color error of the image is observed at angles –2 degrees for sample without adding controllable blur.

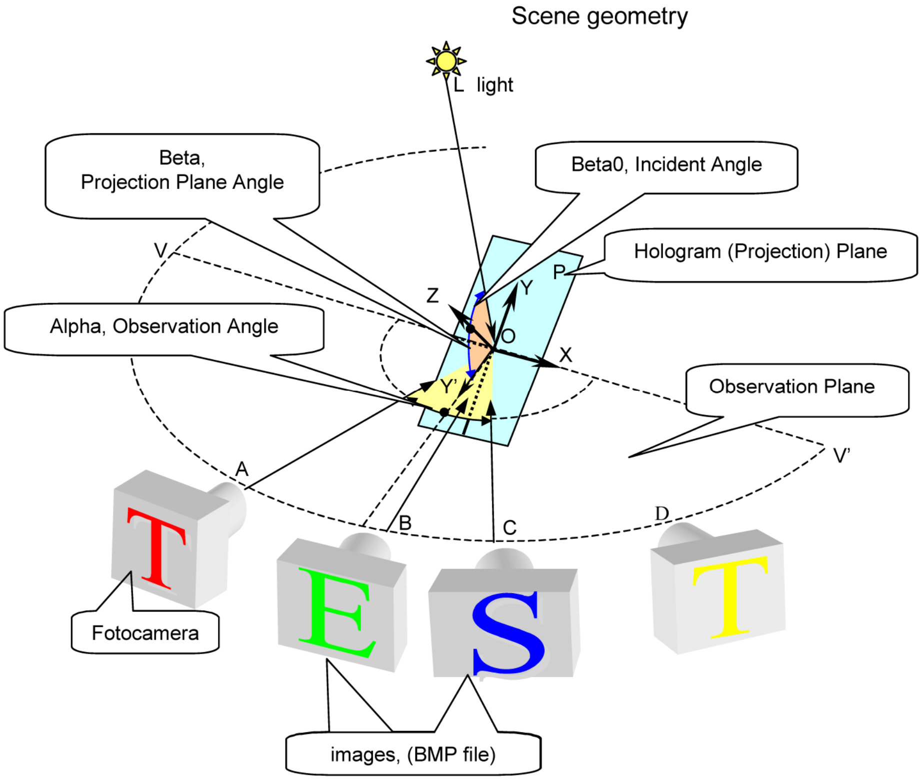

Fig. 12. Scene geometry of rainbow hologram projected from the observer viewpoint.

6. Discussion

Before comparing the proposed approach with the dot-matrix and existing e-beam techniques let us recall the main new features implemented in the new approach. The designing part realizes two methods for proper color synthesis what includes variations of a duty cycle and a grating size. To increase the hologram tolerance to random swinging during observing, a special controllable divergence is added to equalize the blur of all the three pixels used in color presentation. A remarkable feature of the design is flexibility in the pixel shape which now could not only be a square and a rectangle but even not a rectangle at all. The lithographic data is optimized by the considering EBL proximity effect that results in perfect reproduction of the gratings pitch and duty cycle and, as a consequence, in perfect color reproduction. Lithographic data describing a hologram, if stored in common data formats like GDSII, results in an enormous volume of information so a special format for hologram data presentation was developed enabling easy data transfer from a remote place of design to a computer controlling the lithograph. A very important simulation tool is provided which takes only geometry of gratings into consideration. The tool allows looking through and analyzing a future image, which enables optimization of a hologram before real fabrication.

6.1 Comparison with the dot-matrix approach

The history of the dot-matrix technique, the progress of increasing its quality and throughput are described in [19]. The principles and the newest dot-matrix setups including dot-image devices are described in [20]. This is now a mature and widely used technique [24–27].

The main advantage of electron lithography is its unprecedented resolution based on a small electron beam diameter. The resolution exceeds wave limits of optical (dot-matrix) devices of visible range by many thousand times [18]. Combined with a fine control system, the resolution provides high flexibility of writing strategies. Closely packed pixels could be arranged in arbitrary shapes including not only square and rectangular but also those similar to very complicated Escher cells [18].

However, electron lithography is a sequential technique whereas the dot-matrix approach operates in a parallel manner exposing the whole grating. In general, the time per master is a not critical point in the rainbow hologram fabrication and tens of hours per master is acceptable in a production line. Nevertheless, accurate consideration of the throughput of the two techniques show that a dot-matrix machine needs mechanical moving to expose the next pixel and this slows down the rate of writing. Estimates and practical experience showed that a square inch of a rainbow hologram can be produce by SEM-based electron lithography within ten hours which is practically equal to the production time with a dot-matrix device.

Electron lithography provides a higher quality of gratings as is shown by the comparison of the EBL gratings of Figs. 8 and 9 with the best dot-matrix gratings (see Fig. 11 from [20]). Note that Figs. 8 and 9 show 6um gratings whereas Fig. 11 from [20] contains 25um grating. Moreover, no cross-talking of gratings occurs in electron lithography.

As mentioned above the proposed approach includes the addition of blur for equalizing light divergences of R, G, B gratings, which is provided by the curvature of gratings (see Figs. 6, 8 and 9). Such equalizing in divergence is not possible in the dot-matrix technique because the interference scheme allows producing only straight fringes.

Color synthesis in the dot-matrix technique is not perfect in comparison to the approach described here. Two methods are used to control the intensity of R, G, B reflections in the dot-matrix machines: change of grating size and control of grating modulation [20]. The change of the grating size alone without divergence control and blur equalizing results in color error at hologram swinging as was shown above. As to the grating modulation control, this approach can be applied but it is very difficult to realize in practice. Resists which are usually used have a very high contrast and this leads to a very low tolerance of the production process to errors in the exposure dose, temperature, time of development, etc. The low tolerance was the reason why the grating modulation control was not even included as a standard function for color synthesis in the described approach although electron lithography uses 3D shaping for fabrication of kinoform diffractive optics and computer generated holograms [28, 6].

Dot-matrix technique can be simulated with RainBow software by eliminating controllable blur and using the gratings size change only at color synthesis. These simulations show that even a slight inclination (−2 degrees) result in very strong color error.

So one can consider grey-tone hologram as a new security element, which cannot be reproduced with dot-matrix techniques.

6.2 Comparison with industrial e-beam lithographs

Obviously, the main advantage of the proposed approach in comparison to electron lithography with industrial machines is cost reduction. Roughly the system based on the SEM column, EBL controlling system NanoMaker and special “RainBow” software is about ten times cheaper than the usage of industrial lithographic machines. But some topics should still be discussed in relation to the usage of industrial devices.

It is expected that the usage of such machine as lithographs with variable beam shape could decrease time of stamp fabrication but rainbow holograms are a particular case of the objects for which the technique of variable shape beam (VSB) cannot be applied in full measure. The fact is that the beam in the VBS machine has the shape of a rectangle (with size up to several microns), which cannot be rotated continuously. To realize the 2D/3D effect, stereo effect or kinematics effects, part of gratings should have a slight inclination (see Figs. 6 and 11). To realize such effects (by means of inclination providing) an operator of VBS machine should decrease the beam size to a minimum, which is equal to operating the machine in the mode of Gaussian beam. This reduces the writing speed making it equal to that of the SEM column. So, industrial lithographs have no significant advantages in the throughput of rainbow holograms in comparison with the usage of ordinary SEM column.

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Additionally the industrial lithographs are equipped with laser stages to provide perfect stitching of nanometer scale over a size of several inches. Such a stage is not necessary for rainbow hologram production. A hologram consists of distinct gratings and the accuracy of several micrometers available for an ordinary mechanical stage is sufficient.

So, neither in throughput nor in accuracy industrial lithographs have not any advantages in comparison to the described approach based on the usage of on ordinary SEM column.

7. Conclusion

An approach for the fabrication of rainbow hologram designed with the "RainBow" software is presented. The approach is based on electron lithography performed with a SEM column and a special EBL controlling system NanoMaker. The approach of three basic color mixture is used to provide fabrication of full-color digital holograms. The designing tool (”RainBow”) uses the variation of a duty cycle of gratings and size of gratings for proper color synthesis. To increase the color picture tolerance at swinging, a method of equalizing angular divergence of each grating is developed and implemented. The approach allows one to fabricate gray-tone hologram (containing white color) what increases level of hologram security.

For EBL data preparation and optimization, a special design/simulation system "RainBow" was developed.

It is shown that the approach allows the fabrication of rainbow holograms of high quality with a higher tolerance to hologram swinging. The results of fabrication of large rainbow holograms from design to imprinting are presented.

The comparison with existing techniques such as dot-matrix and EBL with industrial lithographs clearly demonstrates the advantages of the described approach.