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IMAGING PROPERTIES OF COMPUTER-GENERATED HOLOGRAMS: THE PHASE DISTRIBUTION EFFECT IN THE OBJECTS' SPACE

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In the paper, the influence of phase distribution over the objects' space on resolution and depth of field of computer-generated holograms has been investigated. The study was carried out through mathematical simulation of real physical processes of synthesis and reconstruction of binary transparent holograms. The possibility of a significant increase (up to several times) in the resolution and depth of field of the reconstructed image because of using phase-shift masks was found. Moreover, this increase was achieved due to representation of the object wave in hologram synthesis as a superposition of object waves emanating light from two identical objects located at different, strictly fixed distances from the hologram synthesis plane.

Keywords: synthesized hologram, binarization, threshold processing, depth of field, phase mask

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ВЛИЯНИЕ РАСПРЕДЕЛЕНИЯ ФАЗЫ В ПРОСТРАНСТВЕ ОБЪЕКТОВ НА ИЗОБРАЖАЮЩИЕ СВОЙСТВА СИНТЕЗИРОВАННЫХ ГОЛОГРАММ

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В работе изучено влияние распределения фазы в пространстве предметов на разрешающую способность и глубину резкости синтезированных голограмм. Исследование проведено методом математического моделирования реальных физических процессов синтеза и восстановления голограмм бинарных транспарантов. Установлена возможность существенного (в нескольких раз) увеличения разрешения и глубины резкости восстановленного изображения благодаря использованию при синтезе голограммы фазовых масок и представлению объектной волны в виде суперпозиции объектных волн, исходящих от двух одинаковых объектов, расположенных на различных, строго фиксированных расстояниях от плоскости синтеза голограммы.

Ключевые слова: синтезированная голограмма, бинаризация, пороговая обработка, глубина резкости, фазовая маска

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Introduction

Holography is widely used in electronics, microtechnology and other spheres. In addition to well-known holographic methods of protection against counterfeiting of goods, holographic diffraction gratings, complex wave front shapers, sights, three-dimensional projection, and other holographic technologies can be applied in photolithography.

The advances of holography in projection photolithography is primarily due to the possibility of simultaneous aberration-free reconstruction of large-sized real images, including images of binary two-dimensional transparencies, namely, photomasks [1 – 3]. The application of holograms in projection photolithography makes it possible to avoid the usage of sophisticated optical systems, complex in design due to strict requirements for quality of the images formed using a photolithographic lens. In particular, the current tendency of size reduction of electronic devices leads to gradual increase in resolution of optical systems. This is usually achieved by reducing the operating wavelength, which in turn leads to a reduction in the size of the aberration-free area of an image.

Particularly noteworthy is the possibility of using images of photolithographic objects of computer-generated Fresnel holograms as projectors, which are a set of discrete pixel-cells with different phase and intensity values and can be easily calculated using modern computers and displayed on physical media. The methods of hologram synthesis for extreme ultraviolet, as well specific requirements for synthesis scheme parameters that would allow to reconstruct a high-quality image were presented earlier [4 – 6].

Imaging properties of the computer-generated holograms in some cases differ from the properties of analog holograms and have their own characteristics. These features are well studied and exist primarily due to the discrete structure of the hologram and image [7 – 11].

This paper presents our findings of the phase distribution effect in the objects' space during synthesis of the Fresnel holograms on its resolution and depth of field of the image formed using these holograms. Real physical processes of synthesis and reconstruction of reflection holograms have been mathematically simulated.

The discrete object-transparency is usually presented as a set of coherent point sources with each source emanating light uniformly in all directions. In this case, the ratio between the values of the amplitude at two selected points on the hologram registration plane is determined by the ratio of the areas of the spheres on which the points are located (Fig. 1). Thus, if the amplitude located at a point on the normal and restored from the source to the hologram plane is taken as a unit, it becomes possible to determine the amplitude at any point on the plane.

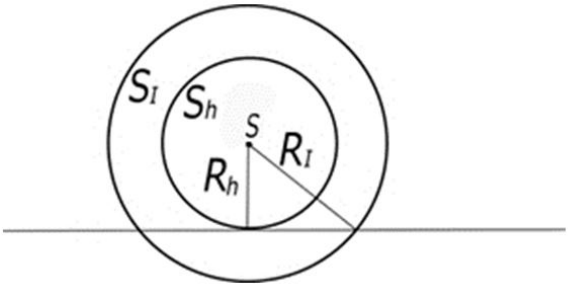

Fig. 1. Distribution of amplitude from a point source (s) emanating light over the hologram registration plane (a straight line);

R_l, R_h are the spherical radii of light rays;

S_l, S_h are the spherical areas

Furthermore, since all the point sources making up the object are coherent, the phase shift from the source to the point on the hologram also depends solely on the radius of the sphere R_l and the wavelength λ:

$$\varphi_l = \frac{2\pi R_l}{\lambda} + \varphi_0 \tag{1}$$

where φ_0 is the initial value of the light source phase.

The final value of the amplitude at each point on the hologram plane is defined as the vector sum of the amplitudes from all points of the object, taking into account distances between the point of the object and the point on the hologram. At the same time, the structure of the hologram and the image formed are significantly influenced by initial phase distributions during hologram synthesis in the object space.

The phase distribution effect in the object's space on the resolution of computer-generated Fresnel holograms-projectors

The phenomenon of the overlap between diffraction maxima from closely spaced elements of the object which leads to resolution lowering is called proximity effect. To correct it, it is proposed to apply a method like the one used in traditional projection photolithography: the installation of phase-shifting masks in the object space, which makes phase difference between wave fronts that form images of neighboring elements of the object structure equal π [12]. Since the synthesis of holograms is performed in virtual space, this could be achieved through the correction of the mathematical model of the photomask, i.e., the introduction of the necessary phase modulation in its transmission function.

Let us find out the applicability limits of the proximity effect compensation method, i.e. conditions under which the elements of the structure of the photomask can be considered neighboring, so that the method under consideration would have a positive effect on the quality of the reconstructed image. This could be done either by diffraction integral calculation, or experimentally, for example, by using mathematical simulation. It was carried out in a software package for synthesis and digital reconstruction of Fresnel holograms [4]. The research included a series of numerical experiments of synthesis and digital reconstruction of the phase-relief reflective Fresnel hologram of a flat object: two slits located closely in a non-transparent screen. It was assumed that the effectiveness of the method for correcting the proximity effect should depend on the distance between the slits.

The parameters for the hologram synthesis scheme were selected based on the requirements described in Refs. [5, 6]. Thus, laser wavelength λ was 13.5 nm; the pixel size of the object and the hologram d_d was 20 × 20 nm. The characteristic size of the minimum element of objects' structure was 80 nm. The pixel size of the object was chosen to satisfy the requirements of the Rayleigh criterion [5]. The angle of the parallel reference beam incidence was chosen equal to 14.7 ° in all experiments, and the distance between the plane of the object and the plane of hologram registration was $R_h = 20345$ nm.

The influence of proximity effect on image quality for different distances between the structural elements of the object was studied by synthesizing and digitally reconstructing the holograms of two slits of 4 × 40 pixels, i.e., 80 × 800 nm each. The resulting numerically reconstructed images are shown in Fig. 2. According to the Rayleigh criterion, two point-sources (in this experiment, narrow slits could be considered as point sources) are completely resolved if the diffraction maximum of one of them is superimposed on the diffraction minimum of the other. Therefore, experiments should be carried out only for those distances between slits that are smaller than Rayleigh resolution criterion for coherent radiation, which is equal to 57 nm for the slits under study.

Thus, the distances between the slits in the experiments ranged from 1 to 2 pixels, i.e. from 20 to 40 nm. Two holograms were synthesized for each of the indicated distances between the slits – one for the case when all the radiation incident on the object was in phase, the other for the case when the beams incident on slits were out of phase. Thus, four holograms were synthesized, and the corresponding images were numerically reconstructed.

To assess the quality of the reconstructed images, we used a method based on comparing the number of threshold processing levels, which imitates photoresist response to actinic radiation exposure. Since the pixels of reconstructed images are encoded using 8 bits, the total number of possible threshold processing levels (intensity gradations) is 256, from 0 (black) to 255 (white), in accordance with so called "gray scale" [13]. So, the greater the number of threshold processing levels (gradations) at which the intensity distribution on the image is identical to intensity distribution on the object, the higher the quality of reconstructed image. The eligibility of using this criterion is explained by the threshold properties of photoresists. The larger the number of acceptable threshold levels for the reconstructed image, the larger the range of exposure doses is permissible in the photolithographic process.

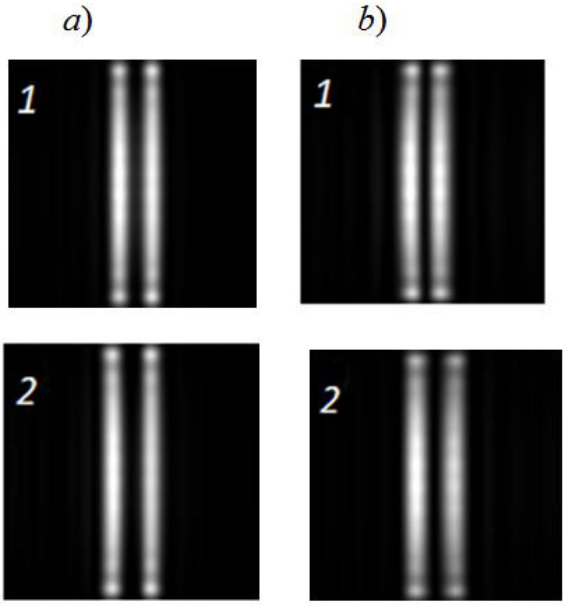

Fig. 2. Reconstructed images obtained with in-phase (*a*) and out-of-phase (*b*) radiation for two distances (nm) between segments: 20 (*1*) and 40 (*2*)

Images reconstructed using holograms recorded with all incident radiation being in phase, corresponded to the original objects in the interval of zero gradations of threshold processing at a distance between slits of 20 nm and 12 gradations at 40 nm. With waves incident on slits being out of phase, the image corresponded to the original object in the range of 14 gradations with a distance between slits of 20 nm and 17 gradations at 40 nm. Thus, in the case of the smallest possible distance between the slits (20 nm), the use of phase masks makes the slits resolvable, while if the distance between the slits is 40 nm, its quality is almost the same regardless of using the phase masks.

Thus, numerical experiments have shown that the application of the phase correction method for the proximity effect allows one to successfully resolve structural elements of the object that are at the minimum possible (equal to the size of the object's pixel) distance between them.

The phase distribution effect in the object's space on the depth of field of the computer-generated Fresnel holograms

The image is considered to be sharp within the limits of such a displacement of the observation plane, at which the diameter of a point object image represented as a geometric point does not exceed the Airy disc diameter. The expression that allows the depth of field of the optical system to be determined in accordance with this criterion is presented as [14]:

$$|b| = \pm \frac{\lambda n}{2A^2} \tag{2}$$

where A is the system numerical aperture, λ is the wavelength of the laser used, n is a refractive index of a medium, equals 1 for air.

Thus, the numerical aperture of the radiation diffracted on the smallest element of the object structure, a pixel with the size a_t, is described as follows:

$$A = n \sin\alpha = \frac{\lambda}{a_t} \tag{3}$$

where α is the aperture angle of the diffracted radiation.

From Eqs. (2) and (3) the only parameters affecting the depth of field are the operating wavelength λ and the size of one pixel a_t. Currently, various methods are known to further increase the depth of field of images. In particular, there are methods based on phase-shift masks [15], modifications of optical devices

[16], special digital processing of images at the stage of their registration [17].

However, not all these methods are suitable for photolithography. The best results in this case can be obtained by the method based on representation of an object wave during the hologram synthesis as a superposition of several object waves generated by the same object, a photomask, located at different distances from the hologram [18].

In this case, the increase in the depth of field of the reconstructed image is due to the fact that the hologram restores not one, but several images with a small offset, not exceeding the depth of field. Since the objects used are flat, the sequence of such images will be perceived as a single image with an increased depth-of-field.

Practical implementation of the hologram synthesis mentioned above requires representation of the object beam as a superposition of two or more object waves generated by the same objects. Such an operation would require a very precise installation of objects during the physical registration of the hologram, inversely to holograms synthesized in virtual space. The distance between flat objects leads to a certain phase difference between the object waves, which obviously affects the recorded hologram structure, the final intensity distribution in the reconstructed image and, accordingly, and the depth of field. In this case, the reconstructed image has the best quality when the object beams are fully in-phase.

If the object and the reconstructed image are in-phase, as proposed above, then the reconstructed images has a constant phase difference in each plane of the image space. If the wavelength is considered as a constant, then the only factor affecting the phase difference between the object waves is the distance between the planes of the objects.

These data are almost completely consistent with the results of phase distribution in the reconstructed image [18]. It should be noted that for small distance values Δ between objects, the main factor affecting phase distribution in the hologram synthesis plane is the point position on the hologram relative to its axis. At the same time, as the Δ value increases, the influence of the point position gradually decreases and the distance between light sources becomes the main factor affecting the phase difference.

Another equally significant factor is discretization. Theoretically, the value of the complex amplitude calculated at a particular point is actually set for the entire pixel due to the limited size of discrete cells of the hologram plane, calculated with Eq. (3). This leads to uncertainty and, as a consequence, to an increase in difference between the recorded values of the phase and the complex amplitude and the real value, as it shifts from the center of the pixel to its boundaries. Note that an offset of one spatial period leads to a phase shift of the reconstructed image of 2π [11]. A sharp change in the phase and amplitude values occurs at the boundaries of adjacent pixels.

The relationship of distance between the object planes and the quality of the reconstructed image was demonstrated experimentally with the above mentioned software package. Experimental evaluation included the synthesis of half-tone Fresnel holograms of the test object called “corners”. The object is shown in Fig. 3,*a*.

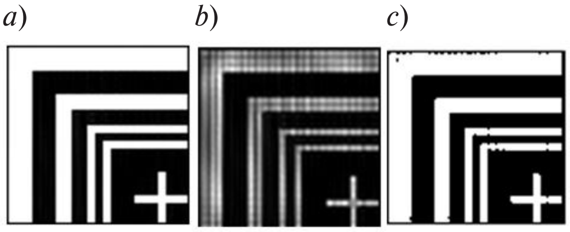

Fig. 3. The original image of the test object (*a*) and the image reconstructed using a synthesized hologram: before (*b*) and after (*c*) threshold processing

The test object was characterized by cross-lines of 1 × 7 pixels. Two corners closest to the cross were made up of 1 pixel-thick segments, the distance between them equaled 1 pixel. This was followed by a gap of 2 pixels in width, and a third corner with 2 pixels in width. The width of the fourth corner was 3 pixels. The total size of the object was 23 × 23 pixels.

The synthesis parameters were chosen in

accordance with the conditions defined in [11] and generally coincided with the parameters used in the previous experiment. That is, the size of the minimum element of the object was 80 × 80 nm, the pixel size of the object planes and holograms d_d was 20 × 20 nm, and the wavelength λ was 13.5 nm. Under such conditions, the angle of incidence of the reference beam α was 14.67°, and the distance between the hologram and the plane of the nearest object was at least 20345 nm. Since the structure of the object is rather complex, R_h value was doubled to 40690 nm. The distance was increased two times to avoid overlapping of restored orders of diffraction. This step is needed to address the problem of interference which starts to influence the quality of the image when high resolution is applied [5]. The depth of field of the reconstructed image at the parameters specified above were $b = \pm 237$ nm, according to Eq. (3).

The second plane of the object was placed a little farther from the hologram at some distance Δ relative to the first, with this distance changing during the experiment.

The reconstructed image quality estimate was carried out using the method based on comparing the number of threshold processing levels described above. The only difference was that due to the high resolution on the reconstructed image, it was considered identical to the object not only when their intensity distributions were the same, but also when the difference between their intensity distributions did not exceed 15 %.

Fig. 4 shows dependence between the allowable levels of threshold image processing obtained in the plane of the best installation at a distance R_h related to the maximum number of gradations achieved with the above described hologram synthesis and reconstruction, and the distance Δ between the planes of two objects.

As long as the Δ value remains sufficiently small (within several wavelengths), the image quality as a whole is not strongly dependent on Δ. The exceptions are the individual maxima corresponding to the object images with higher quality, characteristic of the distances, at which the registered object waves are in phase in the synthesis process. Thus, the minima on the chart correspond to the distances at which the object waves are out of phase.

As Δ increases, the values of the minima approach zero: the influence of the aperture can no longer compensate for the violation of in-phase. As a result, restoration of a high-quality image using such holograms becomes almost impossible. At the same time, the in-phase recording of object waves in absence of the aperture influence can significantly improve the image quality. The “phase uncertainty in hologram synthesis” described above leads to abrupt transitions between adjacent minimum and maximum due to abrupt changes in phase values.

At large distances Δ, close to b, the influence of the hologram aperture practically disappears: the image quality is, on the average, noticeably lower, except for individual maxima arising from the in-phase recording due to the influence of discretization.

The distance between the adjacent maxima corresponds to the working wavelength λ; thus, checking a series of values when shifting within the wavelength, allows to accurately determine the position of the maximum.

To directly estimate the depth of field of the reconstructed images using holograms synthesized at given Δ values, a series of images was reconstructed at distances δ different from the distance R_h by values from −1000 to +1000 nm with a step of 50 nm. The results of the study of image quality in gradations, normalized by their maximum number, are shown in Fig. 5.

Thus, it was established that the addition of a second object plane, provided that the phase of the object waves coincides, made it possible to increase not only the depth of field, but also the overall image quality (maximum number of gradations). The best quality of the reconstructed images was achieved by installing the second plane of the object at distances close to the b value of the limiting depth of field, in this case the depth of field of the image increases by 2 times.

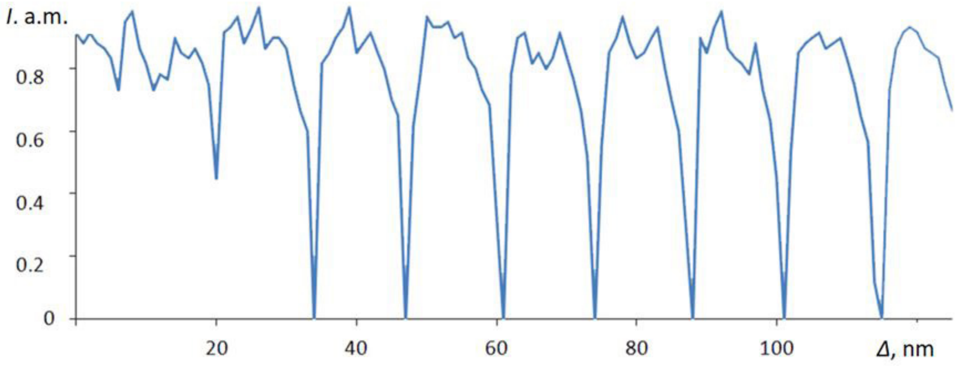

Fig. 4. Graph of the quality of the image of the test object obtained in the plane of the best installation vs the distance Δ between the planes of the objects during the synthesis

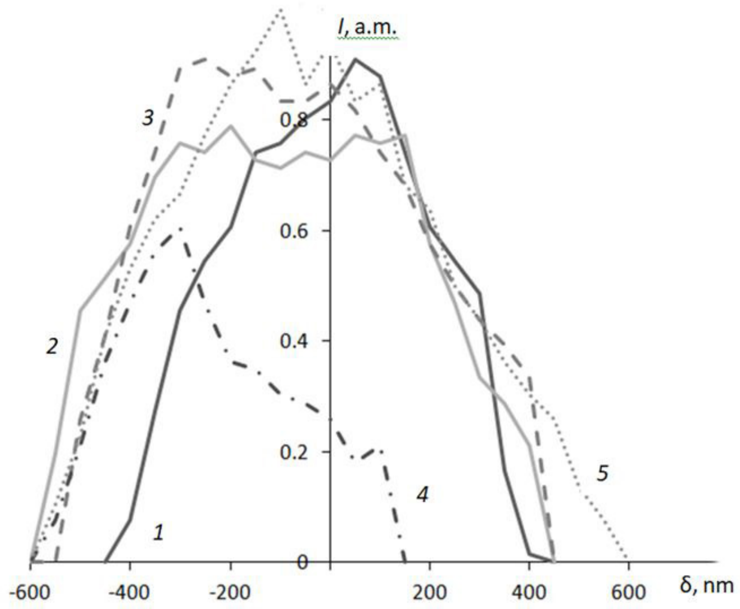

Fig. 5. Graphs of the quality of the test object's image reconstructed vs. defocus δ for different Δ values, nm: Δ = 0, i.e., without installing the second plane (*1*), Δ = 4 (*2*), 21 (*3*), 194 (*4*), 199 (*5*);
Δ is the distance between the planes of the objects during the synthesis

Summary

In this paper, the influence of phase distribution in the object's space on the quality of the images reconstructed from computer-generated Fresnel holograms has been studied. The main features of image formation were considered and the factors affecting their resolution and depth of field were identified. It was established that modifications of the structure of the digital hologram, inaccessible to holograms recorded by traditional methods, could significantly improve the image quality. In particular, the use of phase correction of the proximity effect allows to resolve features being as close as one pixel to each other. Installation of the second object plane in addition to the original one made it possible to increase the depth of field up to 1.5 – 2.0 times depending on the distance between planes.

The results obtained can be used for recording and reconstruction of holograms in real physical space.

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