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Microstructure formation on the basis of computer generated hologram

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1. Introduction

Holograms are important in the areas of scientific research, medicine, commerce and industry. In mass production it is essential to use high-quality originals to make high-quality replicas. In order to do that new methods of production and development are created. One of such new methods of production and development is Computer-generated hologram (CGH).

Computer-generated hologram is described mathematically by computing the phase and amplitude information of the wave propagation produced by an object. There are many applications which use CGH, such as diffractive-optical elements for storage of digital data and images [1], precise interferometric measurements [2], pattern recognition [3], data encryption [4] and three-dimensional displays [5]. One advantage over conventional holograms produced by optical means is that the object used for recording CGH holograms does not need to exist, i.e. it may be described mathematically.

CGH are usually generated using commercial software like MATLAB, MATHCAD, Mathematica and etc. Compared with optical holography, CGH is flexible in design and has good repeatability. Conventional CGH fabrication method requires a number of steps, including wavefront sampling, data calculating, spatial coding, map printing and photo reduction and etc. For CGH creation, usually Fourier algorithm and its various modifications are used. Different technologies have been used to fabricate computer generated holograms and diffractive optical elements (DOE) over a variety of substrates [6–8]. CGHs may be recorded with various materials, such as photorefractive materials, photopolymers and thermo-plastics [9-10].

With respect to their fabrication, phase-only CGH have been highly investigated since they are more light efficient. Phase holograms with a continuous phase profile (kinoform) provide higher diffraction efficiencies [11]. However, elements with multiple phase levels usually require a multistep fabrication process, with the consequent disadvantage in terms of time consuming and the strict requirements on multimask alignment and etching accuracy [12-15]. Therefore, due to its fabrication simplicity and reduced cost, binary phase holograms continue to be very attractive [16]. Many high quality fabrication techniques have been used for creation of CGH, including e-beam lithography [17, 18], photolithography [19, 20] or laser ablation [21, 22]. The quality of the fabricated CGH is reflected in the values of the diffraction efficiency [23].

In this paper, modified Fourier transformation algorithm for creation of CGH is presented. Created CGH was recorded onto a medium that was able to modulate the interference pattern from a coherent light source to produce a reconstructed image.

2. Gerchberg-Saxton algorithm

In previous researches for CGH production, Fourier transformation has been used [24]. The intensity of the hologram points were specified in the coordinates (k, l), where the Fourier transformation of the function h_{mn} was performed

$$H_{kl} = \sum_{m=0}^{M-1}\sum_{n=0}^{N-1} h_{mn} exp\left[-i2\pi\left(k\frac{m}{M}+l\frac{n}{N}\right)\right] \quad (1)$$

Function h_{mn} denotes the intensity of the point of original image.

The Gerchberg-Saxton (GS) algorithm is an iterative Fourier-transform-based algorithm that calculates the phase required at the hologram plane to produce a predefined intensity distribution at the focal plane. Unlike the gratings and lenses approach in which the phase between the traps is fixed, this algorithm provides phase freedom by iteratively optimizing both, the hologram and the image plane phase values. Because beam shaping is limited to the focal plane, only 2D intensity patterns can be generated. A predefined intensity pattern, $I_d(x_i, y_i)$, can be anything from a single dot to a completely arbitrary distribution. The end goal is to find the phase at the hologram plane so that

$$I_d = FFT\{exp[\phi(x_h, y_h)]\}^2 \quad (2)$$

(here FFT – fast Fourier transformation) which will result in the desired pattern being transferred to the image plane. The algorithm is initialized by assigning a random phase, ϕ_r, and unit amplitude to the hologram plane. The first step of the algorithm is given by

$$u_{h,1} = exp(i\phi_r) \quad (3)$$

This field is next propagated to the image plane by taking its Fourier transform. This is done during each of n iterations as:

$$u_{n,i} = FFT\{u_{h,n}\} \quad (4)$$

Then the phase from the resulting complex field at the image plane is retained, and the amplitude is replaced with amplitude, derived from the desired intensity

$$\phi_{i,n} = arg(u_{i,n}) \quad (5)$$

$$u^*_{i,n} = \sqrt{I_d} exp(i\phi_{i,n}) \quad (6)$$

By taking the inverse Fourier transform of Eq. (6) the field is propagated back to the hologram plane

$$u^*_{h,n} = FFT^{-1}\{u^*_{i,n}\} \quad (7)$$

And finally, at the hologram plane, the phase is retained and the amplitude is replaced again with uniform constant amplitude:

$$\phi_{h,n+1} = arg(u^*_{h,n}) \quad (8)$$

$$u_{h,n+1} = exp(i\phi_{h,n+1}) \quad (9)$$

This completes one iteration giving a phase approximation that, when transformed, approximates the desired intensity. The algorithm quickly converges after completing roughly a few iterations producing the desired phase, $\phi_h = arg(u_h)$. Moreover, as it was mentioned previously, the algorithm results in a hologram that produces a two dimensional intensity distribution or pattern [25].

3. Results

The process of formation of digital Fourier GS hologram was implemented by means of the program developed within MATLAB.

Fig. 1 Initial grayscale image of the emblem of KTU

The emblem of Kaunas University of Technology (KTU) was selected for experimental research (Fig. 1), because the results could be compared with previous ones from paper [24]. CGH was created by applying Fourier transformation with GS algorithm (Fig. 2). The algorithm was run for 100 iterations.

Generated hologram (Fig. 2) was checked using the inverse Fourier transformation (Fig. 3). A program was developed with MATLAB for the purpose of reconstruction of the hologram. In the holographic map (Fig. 2) black color means a particular place (point, mark) that is not displayed. The white color means the maximum doze (the map has 8 levels).

Electro beam lithography has been used for the formation of CGH in to multilayer structure polymethyl methacrylate (PMMA) – silicon (Si) (Fig. 4). The size of the CGH is 2.048x2.048mm (or 1024x1024 pixels).

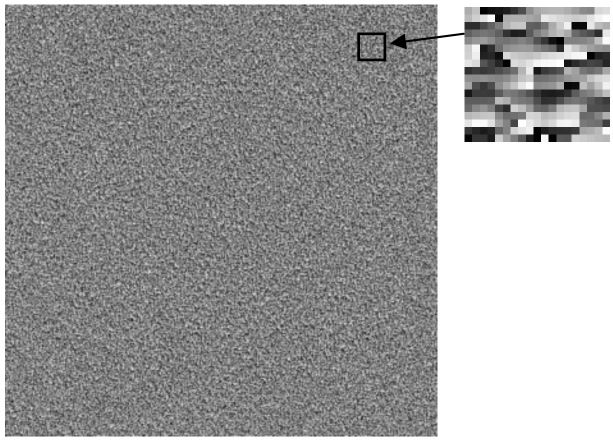

Fig. 2 Computer-generated hologram

Fig. 3 Reconstructed CGH

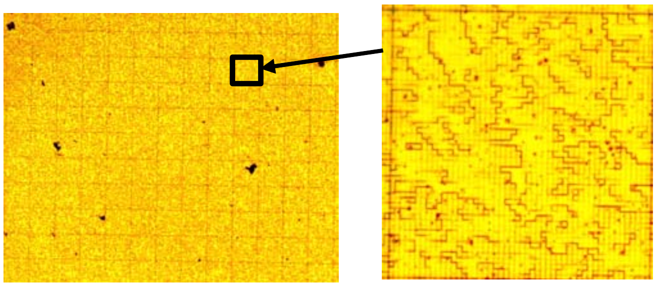

Fig. 4 Photo of the CGH exposed on PMMA

Fig. 5 Fourier GS CGH reconstructed using laser of $\lambda = 633$ nm

Final product of CGH was tested optically and compared with previous results. Photo of reconstructed image obtained from the metalized array is presented in Fig. 5 (laser wavelength $\lambda = 633$ nm). Optical result is much better than CGH is created using Fourier transformation (Fig. 6).

Using the Fourier transformation, the reconstructed CGH (Fig. 6) has only outlines of pictures and two greyscale levels: black and white. When we modified the first model with GS algorithm, the reconstructed CGH (Fig. 5) has greyscale levels and full pictures.

Fig. 6 Fourier CGH reconstructed using laser of $\lambda = 633$ nm [24]

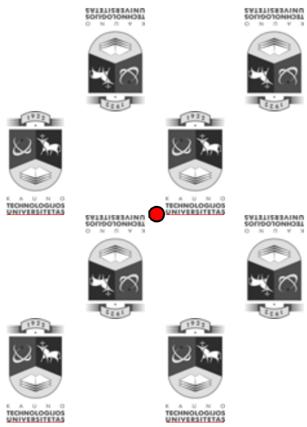

Fig. 7 Distribution of the diffraction maximums of the reconstructed Fourier CGH (laser spot is marked in the centre)

Fig. 8 Distribution of the diffraction maximums of the reconstructed Fourier GS CGH (laser spot is marked in the centre)

Diffraction efficiency of CGH increases approximately 6 times (from 8% for Fourier CGH to 45% for Fourier GS CGH). Also differences in the distribution of diffraction maximums were observed (Figs. 7, 8).

4. Conclusions

Gerchberg-Saxton algorithm was implemented in to the modelling process of CGH. This algorithm increases diffraction efficiency of CGH approximately 6 times (from 8% for Fourier CGH to 45% for Fourier GS CGH). Also modified Fourier transformation with GS algorithm introduces greyscale levels into hologram and lets completely to reconstruct the image.

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MIKROSTRUKTŪRŲ FORMAVIMAS NAUDOJANT KOMPIUTERIU GENERUOJAMAS HOLOGRAMAS

R e z i u m ė

Straipsnyje aprašoma, kaip taikant Furjė transformaciją, kuriama Kauno technologijos universiteto ženklo kompiuterinė holograma ir kaip ji suformuojama PMMA, naudojant elektroninės litografijos techniką. Kompiuterinių hologramų sintezei panaudotas Gerchbergo ir Saxtono algoritmas, bei pateikta šių kompiuterinių hologramų pavyzdžių.

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MICROSTRUCTURE FORMATION ON THE BASIS OF COMPUTER GENERATED HOLOGRAM

S u m m a r y

Implementation of computer-generated hologram of the emblem of Kaunas University of Technology by means of Fourier transformation from greyscale image, and transferring of the hologram to PMMA using electronic lithography are analyzed in this paper. Gerchberg-Saxton algorithm of synthesis of computer generated hologram and sample of computer generated hologram are presented as well.

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ФОРМИРОВАНИЕ МИКРОСТРУКТУР НА ОСНОВЕ ГЕНЕРИРУЕМЫХ КОМПЬЮТЕРНЫХ ГОЛОГРАММ

Р е з ю м е

В настоящей работе приведено исследование генерирования компьютерных голограмм используя Фурье трансформацию, а также трансформирование голограмм на PMMA при помощи электронной литографии. Для генерирования компьютерных голограмм использован алгоритм Gerchberg-Saxton, представлены образцы генерированных компьютерных голограмм.

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